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Experimental Studies of Graphite-Epoxy and Boron-Epoxy Angle Ply Laminates in Shear

by

T. Weller

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HAIFA 32000, ISRAEL

for

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ABSTRACT

This report describes and presents a test program carried out at NASA Langley Research Center aimed at defining the nonlinear/inelastic response under inplane shear of a large variety of 3M SP-286T3 Graphite-Epoxy and AVCO 5505/5.6 Mil. Dia. Boron-Epoxy angle-ply laminates, as well as obtaining their strength allowables and detecting the mechanisms which govern their mode of failure. Two types of specimens for the program were chosen, tested and evaluated: shear panels stabilized by an Aluminum Honeycomb core and shear tubes. A modified biaxially compression/tension loaded "picture frame" was designed and utilized in the test program with the shear panels. Evaluation of the experimental results, i.e. the type of experienced stress-strain field and strength values observed for the panels tested with this new apparatus, and comparison of the results with those experienced by the tubes, indicate that the new modified "picture-frame" has fulfilled and justified the expectations and proved to be an adequate and reliable device for inplane shear testing. The results obtained with this test technique categorically prefer the shear panels, rather than the tubes, for adequate and satisfactory experimental definition of the objectives concerned with the present test program. The present test results indicate the existence of a so-called "core-effect" which ought to be considered when reducing experimental data for "weak" in shear laminates.

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LIST OF SYMBOLS

a	End tabs length, Fig. 1B.
Gxy	Inplane Shear Modulus.
(Gxy)nom.	Inplane Shear Modulus corresponding to laminate nominal thickness.
Gxy_i	Inplane Shear Modulus corresponding to $(i)^{th}$ loading cycle.
L	Shear tube length, Fig. 1B.
$M_{ULT.}$	Ultimate torque.
M_i	Torque corresponding to $(i)^{th}$ loading cycle.
O.D.	Shear tube Outside Diameter, Fig. 1B.
$P_{COMP.}$	Compression load introduced into "picture frame".
$P_{TEN.}$	Tension load introduced into "picture frame".
t	Laminate thickness.
α	Lamina angle.
γ_{xy}	Inplane shear strain.
$\gamma_{max.}$	Laminate max. inplane shear strain at failure.
σ_{xy}	Laminate inplane shear stress.
$\tau_{ULT.}$	Ultimate inplane shear stress.
$(\tau_{ULT.})$nom.	Ultimate inplane shear stress corresponding to laminate nominal thickness.
$(\tau_{ULT.})$measur.	Ultimate inplane shear stress corresponding to laminate measured thickness.

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1. INTRODUCTION

The present report provides the results of a test program accomplished at NASA Langley Research Center, aiming at the investigation of the nonlinear and inelastic shear response of Graphite-Epoxy and Boron-Epoxy laminates across a wide range of laminate configurations.

One of the main types of loads that aerodynamic as well as space structures are exposed to, is shear loading. In designing with advanced composite materials to sustain shear loading, the extra "parasitic" weight introduced when utilizing conventional materials can be eliminated. It is their "tailoring" capability which makes composites advantageous, relative to other materials, for carrying this type of load, but only if appropriately designed so as to recognize that the "strong" in shear laminate might experience a very "poor" response, and possess "poor" properties to withstand the other types of loading the structure experiences during its missions (see for example [1]). This calls for an intensive investigation of a large variety of laminate configurations to obtain their responses, particularly in the inelastic region, their strength allowables, and to detect their modes and mechanisms of failure; this will assess in defining an intermediate "least penalty" in shear laminate configuration for a particular design purpose.

It is the objective of the present test program to establish and furnish experimentally the abovementioned vital information as well as comparing the observed empirical results with theoretical predictions yielded by existing analyses. The present test results will also provide better physical insight to justify and evaluate the postulations and assumptions made in the development of the theoretical studies. The present test program also underakes to evaluate and develop as well as recommend both better and preferred test techniques and types of specimens to study the objectives concerned with the present test program.

The report details the results obtained for 13 shear panels (S.P.) and 19 shear tubes (S.T.) fabricated from Graphite-Epoxy, and 12 shear panels and 18 shear tubes made of Boron-Epoxy. All the

laminates were fabricated from unidirectional prepreg tapes, and laid up symmetrically. The specimens were designed to avoid buckling as well as failure of the loaded edges, and thus exhibit a strength mode of failure of the laminate itself.

2. EXPERIMENTAL INVESTIGATIONS

2.1. TEST SET-UPS AND PROCEDURES

2.1.1 Shear Panels

The shear panels (S.P.) were loaded by the so-called "Modified Picture Frame", Fig. 2A, described in detail in [2]. It differs from the commonly used picture frame by the fact of being loaded biaxially: tension (with a 300 kips Tension-Compression Machine) in one direction, and compression (with a specially designed system) in the transverse direction, with the loads being equal in magnitude and applied simultaneously. This type of loading results in:

(a) Avoidance of bending of the frame members.

(b) Elimination of shear lag so that the load is sheared uniformly along the edges of the specimens without the necessity of tapering the frame members.

(c) Reduction by half of the capacity of the tension machine and consequently the high stresses experienced by the heavy corner pins of the frame and other loading pieces. Its shortcomings are mainly operational ones: being expensive due to high precision requirements in its manufacturing process. Also each specimen has to be individually handled and prepared prior to testing, which is time consuming, and expensive.

The load is sheared from the frame members into the panel by seven 3/8" bolts along each side of the frame. The bolts shear their load through steel doublers bonded to the external facings of the panel along its periphery, and heavy steel blocks bonded to the internal surfaces of the laminates and opposite to the doublers. To assure appropriate and uniform shearing through the bolts and in-plane loading of the panel, the specimen has to be located parallel to the plane of the frame elements. This is achieved by grinding the doubler parallel to the specimen facings prior to drilling the seven 3/8" holes along

the edges of the specimen. Then the holes are drilled with the aid of an expecially manufactured template with undersized holes (see also section on specimens). The specimen is now put between the two frames forming the picture frame and bolted with the center bolt along each side (after these holes have been rimmed). The corner pins are also inserted in their place. Then the remaining holes are rimmed with the holes in the frame members guiding the rimmer. (To allow for this the frame members were hardened to R.C.≈35. When this procedure is complete the specimen is delivered for putting strain gages on its facings). Now all the bolts are inserted in the holes, the four yokes carrying the frame and loading the corner pins are put in their place by inserting the heavy corner pins through them, and the frame is hung in the tension machine. The bolts along the sides are gradually and evenly tightened with a torque wrench (to a maximum torque of 35 lb.-in.). Then the transverse loading elements are put in their place and the panel is ready for loading.

Strain gages were bonded to the surfaces of the laminates and recorded during the loading procedure by a multichannel system, to obtain the response of the laminate. In the first stage of testing, 44 gages were bonded to the facings, Fig. 3A (Test 515, Runs 1-7). After carefully analysing the obtained data from these many gages and evaluating the performance of the picture frame, the number of gages was later reduced to 29, Fig. 3B (Test 516, Runs 1-6 and Test 517, Runs 1-10). A detailed discussion on the choice of "satisfactory" gage location is given in [2].

2.1.2 Shear Tubes

The shear tubes were loaded between the end platens of the torque machine, Fig. 2B. They were fastened to specially designed end rigs with 12 bolts at each end (see specimens). These end fixtures have a center hub which is fitted into the center holes of the internal end tabs of the tube. In such a manner the centric axial aligning of the tube in the loading machine is maintained. The torque was applied through these end rigs, Fig. 2B. Some clearance was left between these end fixtures and the platens of the machine, to allow for axial

displacements and avoid the introduction of axial compression stresses into the tube.

17 strain gages were bonded to the surface of the tube, Fig. 3C; 11 of them were placed circumferentially along the center of the tube to record the response of the material, and the other six were placed close to the end tabs to detect any irregular behavior; this was anticipated close to the end tabs and might have caused premature failure of the specimen. These gages also assisted in detecting the existence of components of axial compression due to inappropriate alignment of the tube between the end platens.

Two split end rings were attached to the tubes at their edges, Fig. 2B. These rings had long arms attached to their center and strings connected to their ends. The ends of the strings were hooked up to the moving parts of DCDT's and hence measured the relative rotation of the end cross-sections of the tube to which the rings were attached. Records of the DCDT's were taken to be compared with the average gage records along the center line of the tube.

Many of the tubes were gradually loaded and unloaded in a cyclic manner, in order to find the influence of such a procedure on their response and mechanical properties. Some of the results are presented and discussed in Appendix A.

2.2. TEST SPECIMENS

In the test program six different types of symmetrical laminate configurations were investigated for each material, see Tables 1 and 2. The program consisted of 13 Graphite-Epoxy shear panels; 12 Boron-Epoxy shear panels; 19 Graphite-Epoxy shear tubes and 18 Boron-Epoxy shear tubes. For details and dimensions see Tables 1 and 2.

The laminate facings for the shear panels and laminated cylindrical walls of the tubes were fabricated from unidirectional prepreg tapes: 3M-SP286T3 Graphite-Epoxy A-S(5.0 Mil), .0052"(.013 cm) ply thickness, and Avco 5505/5.6 Mil Dia., Boron-Epoxy, .0067"(.017 cm) ply thickness.

The ultimate load capacity for each laminate configuration was predicted with the aid of the SQ5 computer code [3].

2.2.1 Shear Panels

All the shear panels, Figs. 1 and 2, were made out of 8-ply laminated facing and were stabilized against buckling with a (3/16)" Cell x 5052 x 8.08 #/cu.ft. Al. Honeycomb core to which the laminates were bonded. As already described earlier the load is sheared into the specimen by the 28 bolts inserted through the holes along the edges of the panel. To avoid edge effects the edges of the panel were stiffened by doublers bonded externally to the facings of the panel along their edges and by heavy steel blocks bonded between the facings against the doublers, Figs. 1 and 4. The procedure of drilling the holes along the edges of the panel has already been described above. The holes in the laminated facing under the doublers were drilled prior to bonding of the laminates to the honeycomb core and the edge metal pieces. They are oversized to assure elimination of any bearing stresses between the bolts and laminate, which might result in severe damage to the bolts, especially when Boron filaments are involved. (For more details see [2]).

2.2.2 Shear Tubes

The tubular specimens vary in their wall ply number, see Table 2, to avoid premature failure in a buckling mode. The necessary number of plies was dictated by linear elastic buckling predictions for each laminate configuration, and tube dimensions were calculated with Wu's computer code [4]. An attempt was made to maintain the critical load at buckling, at least twice as high as the ultimate load predicted for the laminate with SQ5 [3]. The load is introduced into the tube laminated wall by shearing through steel end tabs split into three segments and bonded to the external and internal surface of the tube wall, Figs. 1 and 5. Torque is applied on these end pieces by 12 bolts bolted to each end of the tube and to the specially designed end loading rigs discussed above. To avoid premature end failure of the tube and to assure that the laminate exhibits strength failure, the required shearing surface between the steel end pieces and the laminated tube wall to withstand the predicted load with [2] was calculated with a code developed by the manufacurer of the specimens, SWRI [5], and the end tabs designed a accordingly. This of course results in different dimensions of the end pieces for the variety of laminate configurations tested, see Fig. 5.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In Tables 1 and 2 the test results obtained for the shear panels and shear tubes are presented respectively. These Tables report the values of ultimate strength and corresponding maximum strain values achieved during the course of tests for the various laminate configurations investigated, as well as the elastic shear moduli calculated from the reduced stress-strain response corresponding to each of these laminate configurations.

The reduced shear responses of the Graphite-Epoxy shear panels and tubes are shown in Figs. 6A and 6B respectively, and those corresponding to the Boron-Epoxy panels and tubes are presented in Figs. 7A and 7B respectively.

Before discussing in detail the test results obtained for each individual laminate configuration, some common comments in regard to the manner of reduction of the test data and its presentation in the present report for all of the test specimens included in the test program, should be noted:

(a) Each laminate configuration is presented by three types of figures; one for the panels and one for the tubes designated A and B respectively, with each of these consisting of two figures: one presenting the individual responses corresponding to each specimen, and the second being the best fit representation of the abovementioned figure. The third figure represents a comparison study between the abovementioned figures A and B, and is designated as C.

(b) Test data was reduced and curve-fitted according to the following relation: $\gamma = A\tau + B\tau^N$, which is a three parameter relation between the shear strain γ and corresponding shear stress τ, and A, B and N are the parameters to be determind from the curve fitting procedure (this, of course, is the well known Ramberg-Osgood type of nonlinear response).

(c) In [2] stiffening of the sandwich type shear panels due to the stabilizing honeycomb core was recognized. A method to eliminate this so-called "core effect" has been proposed in [2].

The comparison studies of the type C figures mentioned above in (a)

also present the "corrected" response corresponding to the shear panels, i.e. "core effect" eliminated (designated PANELS CORR.), together with the response corresponding to the case where this effect has been ignored (designated PANELS INCORR.). Hence, this figure also evaluates the "core effect" for the various laminate configurations. The "corrected" shear moduli, according to [2], are presented in Table 1.

(d) The stresses employed to represent the empirical results experienced by the tubes in the type B figure mentioned above in (a) are based on the nominal tube wall thickness, i.e. number of plies in the laminate multiplied by nominal ply thickness, rather than on "true" measured thickness, see Table 2. As will be seen later on in the discussion, calculations based on the actual wall thickness, in many cases, have yielded considerably lower ultimate stress values relative to the panels, and hence are felt to be unrepresentative. Being aware of the fact that the laminate is actually thicker due to excess matrix material in the laminate with no additional fiber content, it is assumed that this extra matrix material almost wouldn't contribute any excessive load carrying capacity to the laminate, except to the "weak" in shear laminate configuration, e.g. unidirectional and cross-plied [0°/90°] laminates. However, in the comparison studies of the type C figure a curve corresponding to "true" measured wall thickness of the tubes is shown (designated TUBES T. THICK). Note that the curve corresponding to nominal tube wall thickness is designated in this figure as TUBES NOM. THICK. The moduli values based on the "true" measured thickness are presented in Table 2.

3.1. GRAPHITE-EPOXY LAMINATES

3.1.1 [0°] (Panels) and [90°] (Tubes) Unidirectional Laminates

Fig. 8A presents the responses experienced by the shear panels; Fig. 8B those obtained for the tubes; and Fig. 8c a comparison study between the response corresponding to the panels and that yielded by the tubes, as well as an evaluation of the "core effect" for this laminate configuration. It appears from Figs. 8A and 8B and Tables 1 and 2 that the tubes sustained considerably higher strength values than

did the panels (by about 24 percent), and experienced a slightly higher shear modulus. This is also observed in the comparison study of Fig. 8C. Similar conclusions are drawn from Fig. 8C when considering and comparing the curves representing the "corrected" response corresponding to the panels and that reduced for "true" stresses of the tubes. Also see for comparison Tables 1 and 2. It is also observed in this figure that the panels and tubes respond very similarly up to the failure stress corresponding to the panels.

The main conclusion to be drawn from the comparison study in Fig. 8C is that in the case of unidirectional "weak" in shear laminate one cannot ignore the so-called "core effect" which is observed to extremely alter and affect the response experienced by the laminate, and to considerably reduce the shear modulus, $.57 \times 10^6$ psi relative to $.90 \times 10^6$ psi. Also, the strength is drastically reduced from 8.7 ksi to 6.1 ksi.

Fig. 8B reveals that there is almost no scatter among the results experienced by the individual tubes, whereas Fig. 8A exhibits a considerable scatter among the panels, in particular in the shape of their individual responses. Table 1 indicates that one of the tested panels was damaged prior to testing. This panel corresponds to Test 517, Run 3 of Fig. 8A. It is observed from this figure that the response of this panel was affected by the damage at the region of high stress-strain levels where the behavior appears to be irregular. The strength, however, was unaffected, and it is seen from Table 1 that this panel experienced a higher strength than the panel of Test 516. Due to its irregular behavior the response corresponding to this panel had to be truncated at a stress lower than its ultimate. Note also that this panel response was very much like that of Test 516 up to the stress level where irregularity starts. Fig. 8A also reveals that these two panels responded differently from the panel corresponding to Test 614. Apparently they belong to the same batch, whereas that of Test 614 was manufactured later to replace the damaged panel.

3.1.2 [±15°] Laminates

The responses yielded by the shear panels are shown in Fig. 9A, and those experienced by the tubes in Fig. 9B. A comparison study between the panels and tubes is presented in Fig. 9C. It is observed in Figs. 9A and 9B, as well as Tables 1 and 2, that the tubes yielded a higher ultimate stress and shear modulus than did the panels. It also appears from Fig. 9C that the response of the panels differs completely from that of the tubes, independent of whether the panels are "corrected" for "core effect" or the tubes accounted for in "true" measured thickness. It is seen from Fig. 9C that once the "true" thickness is taken into account, the response of the tubes is similar to that corresponding to the panels where the "core effect" was neglected. Again, as for the [0°] laminate, Fig. 9C categorically denies neglect of the "core effect" for the present laminate configuration, though the reduction in strength and shear modulus is not as pronounced as for the [0°] laminate. Also, the shape of the response is not seriously affected.

3.1.3 [±30°] Laminates

The responses corresponding to the panels and those yielded by the tubes are presented in Figs. 10A and 10B respectively and the comparison study between the panels and tubes is shown in Fig. 10C. It appears from Figs. 10A and 10B that the two types of specimens yielded similar strength values, but the tubes experienced a significantly higher modulus than did the panels (by about 41 percent). However, when the comparison study of Fig. 10C is considered it is observed that when "true" stresses are accounted for in the tubes they respond very closely to the panels where the "core effect" was ignored, but experience a considerably lower strength than that yielded by the panels. This figure also reveals that for the present laminate configuration the "core effect" becomes almost immaterial, and hence may be ignored in analysing the experimental data.

3.1.4 [±45°] Laminates

Fig. 11A presents the responses obtained for the panels; Fig. 11B presents those yielded by the tubes; and Fig. 11C the comparison study between the panels and tubes. It is seen from Figs. 11A and 11B

as well as Tables 1 and 2 that, in comparison to the panels, the tubes experienced a considerably higher shear modulus and consequently a different response (see Fig. 11C). Also these Tables indicate that the nominal ultimate stress corresponding to the tubes is noticeably above that experienced by the panels. However, when the results are evaluated on a basis of the comparison studies of Fig. 11C, it is recognized that the tubes experienced strength values significantly lower than those yielded by the panels, and their response is very similar to those yielded by the panels where "core effect" was eliminated. It is also seen from this figure that, as for the [±30°] laminate of Fig. 10C, the "core effect" is immaterial.

3.1.5 [0°/90°] Laminates

The responses corresponding to the panels are shown in Fig. 12A, and those to the tubes in Fig. 12B. A comparison study between the panels and the tubes is presented in Fig. 12C. It appears from these figures, Table 1 and Table 2, that the panels experienced far higher strength and modulus values than did the tubes (about 57 percent in strength and 53 percent in modulus). It is worthwhile noting that both the panels and tubes responded with a much higher stressing/straining capacity than that experienced by the [0°] laminate configuration. In spite of this it is found that correlation between the responses of the two configurations is very good up to the failure stress of the [0°] laminates.

Fig. 12C indicates a one to one correlation of the tubes (where stresses are based on nominal thickness) with the panels, when "core effect" is unaccounted for, except for the very high straining of the panels relative to the tubes. When "true stress is considered for the tubes, it is found that it influences this type of "excellent" agreement. This figure, as for the [0°] laminates, again reveals the very pronounced effect of core stiffening on the "weak" in shear laminates. Hence, the existence of "core effect" should be recognised when reducing the empirical data of the present laminate.

3.1.6 [0°/±45°/90°] Laminates

Fig. 13A shows the responses yielded by the panels; Fig. 13B those experienced by the tubes; and Fig. 13C a comparison study between the two types of specimens. Figs. 13A and 13B reveal that the tubes responded differently from the panels, experiencing an appreciably higher shear modulus than did the panels (see also Tables 1 and 2). It is also found from Tables 1 and 2 that the tubes yielded considerably higher nominal stresses than did the panels. It is observed in Fig. 13B that there is a significant scatter among the responses yielded by the individual tubes, where there is none among the panels of Fig. 13A. The comparison studies of Fig. 13C show that when "true" stresses are considered for the tubes they respond even less stiffly than the panels for which the "core effect" has been eliminated, and experience strength values considerably below the ones obtained for the panels. It is also apparent from Fig. 13C that "core effect" again gains its importance for the present configuration and hence should be considered when reducing the empirical data.

3.2. BORON-EPOXY LAMINATES

3.2.1 [0°] (Panels) and [90°] (Tubes) Unidirectional Laminates

Fig. 14A presents the responses corresponding to the panels; Fig. 14B those yielded by the tubes; and Fig. 14C a comparison study between the panels and tubes. These figures together with Tables 1 and 2, reveal that the panels experienced considerably higher stress-strain ultimate values relative to the tubes. It is seen from Fig. 14C that excellent agreement exists between the response corresponding to the tubes based on nominal stresses, and that corresponding to the panels with the "core effect" neglected. It is seen from this figure, as well as Tables 1 and 2, that the shear moduli corresponding to these responses are almost alike, whereas the strength of the tubes is appreciably lower than that experienced by the panels. It is also observed in Fig. 14C that there is also good correlation of the response corresponding to the tubes when "true" stresses are considered and that yielded for the panels when the "core effect" is eliminated. In this case the difference in strength values is not as pronounced as that for the representation

discussed above. As before for the [0°] and [0°/90°] "weak" in shear laminates, the response of the present laminate is also influenced extremely by the honeycomb core. Hence "core effect" cannot be ignored in data reduction of the present laminate.

In Fig. 14A peculiar behavior of the panels is observed where at about a stress level of 7. ksi both tested panels exhibit a "yield"-like phenomenon. No such behavior is observed for the tubes of Fig. 14B. Also, no significant scatter of results is noticed up to this stress level, whereas beyond this point scatter of results becomes appreciable.

Fig. 14B reveals some scatter among the responses yielded by individual tubes.

3.2.2 . [±15°] Laminates

The responses corresponding to the panels and tubes are shown in Figs. 15A and 15B respectively, and the comparison study between the panels and tubes is presented in Fig. 15C. It appears from these figures that the panels responded completely differently from the tubes; the response of the tubes based on nominal thickness is considerably stiffer than that of the panels, and hence experienced a shear modulus considerably higher than did the panels (by about 73 percent). However, the strength corresponding to this response is slightly lower than that yielded by the panels (see also Tables 1 and 2). The comparison studies of Fig. 15C reveal that once "true" stresses are considered when representing the response of the tubes, it agrees very well with that yielded by the panels with "core effect" not accounted for, but in this case the ultimate stress is drastically decreased relative to the tubes. The comparison studies of Fig. 15C indicate that a "core effect" still exists for the present laminate and should be considered when analysing the test data.

Figs. 15A and 15B reveal that more pronounced scatter was experienced among the results obtained for the panels than that for the tubes.

3.2.3 [±30°] Laminates

Fig. 16A presents the responses corresponding to the panels; Fig. 16B those yielded by the tubes; and Fig. 16C is a comparison study between the panels and tubes. It is observed in these figures, as well as Tables 1 and 2, that the tubes experienced considerably stiffer behavior than did the panels, but on the other hand sustained lower strength values. It is found from Fig. 16C that when "true" stresses are accounted for in the tubes, they respond only slightly more stiffly than the panels, for which "core effect" was neglected. However, they yield a very low ultimate stress relative to the panels. Fig. 16C also shows that for the present laminate configuration the existence of "core effect" is immaterial and hence can be ignored.

Almost no scatter is observed among the results yielded by the panels in Fig. 16A, whereas a significant scatter exists among the results corresponding to the tubes in Fig. 16B, expecially in regards to the ultimate stress experienced by the tube of Test 539, Run 1 which failed at a very low stress (about 43 percent of the stress corresponding to failure of the tube of Test 535, Run 17, see also Table 2). This tube was tested and torqued with the combined loader of the NASA Langley Research Center, because SQ5 [3] predicted an ultimate torque corresponding to the [±30°] Boron-Epoxy tested tubes, which was beyond the capacity of the machine of Fig. 2B. Similar results were drawn from the stresses experienced by the shear panels. For undetected resons this tube failed under a very low torque, and hence it was decided to test the other tubes in the machine of Fig. 2B. As a matter of fact none of the ultimate torque sustained by these tubes exceeded the range of the machine.

3.2.4 [±45°] Laminates

In Fig. 17A the responses yielded by the panels are presented; in Fig. 17B those experienced by the tubes; and in Fig. 17C the results for both panels and tubes are compared and evaluated. It is found from these figures, as well as Tables 1 and 2, that the panels sustained considerably higher strength values than did the tubes, whereas the tubes responded in a considerably stiffer manner when nominal stresses were considered. Fig. 17C reveals that once "true" thickness of the tube

is considered the tubes become appreciably less stiff than the panels, and their strength is further reduced significantly in comparison to the panels.

It is apparent from Fig. 17C that "core effect", too, is immaterial for the present laminates.

It is observed in Fig. 17A that there is almost no scatter among the results yielded by the panels, whereas Fig. 17B and Table 2 reveal a very pronounced scatter among the ultimate strengths experienced by the individual tubes. It is seen from Fig. 17B and Table 2 that the tube of Test 535, Run 20 yielded a strength value which is about 179 percent and over of the strength values obtained for the tubes of Test 538. Again, as with the [±30°] tubes, these tubes had to be tested in the combined loader because SQ5 [3] predicted an ultimate torque which was beyond the range of the machine of Fig. 2B. Such torques were also expected due to the results experienced with the panels. When testing with the combined loader, the tubes of Test 538 failed under very low torques and hence the third tube was tested in the torque-machine of Fig. 2B.

3.2.5 [0°/90°] Laminates

Fig. 18A presents the responses experienced by the panels; Fig. 18B those yielded by the tubes; and Fig. 18C a comparison study between the panels and the tubes. It appears from these figures, together with Tables 1 and 2, that the panels experienced extremely higher stress/strain and modulus magnitudes in comparison to the tubes when the "core effect" was neglected, hence they responded in a considerably stiffer manner, as can be observed in Fig. 18C. This figure reveals that once the "core effect" is eliminated in the case of the panels and the stresses corresponding to the tubes are calculated on a basis of "true" thickness, the response yielded by the tubes becomes identical with that experienced by the panels up to the failure stress of the tubes. It is observed in Fig. 18C that the response corresponding to nominal thickness of the tubes is only slightly different from that based on the "true" thickness. This figure, like for the previously discussed "weak" in shear laminates indicated that "core effect" cannot be neglected

in dealing with the test data of this type of laminate.

Like the Graphite-Epoxy laminates it is again observed that this type of laminate exhibits a very high straining capability in comparison to the [0°] laminates. It can also be shown that, up to its failure stress, the response corresponding to the [0°] laminates is very much like the present one.

No scatter is observed among the results yielded by the panels in Fig. 18A, whereas a noticeable scatter is found among the tubes of Fig. 18B, particularly observed in the nonlinear region.

3.2.6 [0°/±45°/90°] Laminates

The responses corresponding to the panels and tubes are presented in Figs. 19A and 19B respectively. A comparison and evaluation study of these specimens is shown in Fig. 19C. It is observed in these figures, and Tables 1 and 2, that the tubes experienced very low strength values relative to the panels, but exhibit a considerably stiffer response. It appears from Fig. 19C that when the "true" thickness is accounted for, the tubes become less stiff than the panels. Fig. 19C also reveals the existence of insignificant "core effect". Hence its influence can be ignored when reducing the experimental data.

No scatter is observed among the results obtained from the panels in Fig. 19A, whereas extreme scatter is found among the results yielded by the tubes as regards the strength values, see also Table 2. The tube of Test 538 experienced an ultimate stress of 146 percent which is above the ultimate stresses experienced by the tubes of Test 535. Again, SQ5 [3] predicted for the present tubes an ultimate torque beyond the capacity of the machine of Fig. 2B. Hence the tubes had to be torqued in the combined loader. When it was found that the tube of Test 538 failed under a very low torque, the remaining two were tested in the machine of Fig. 2B and failed even under lower and almost identical torques.

4. CONCLUSIONS

(a) The modified biaxiaxial, tension/compression, "picture frame" designed and built for the present test program displays very good performance, i.e. uniform "pure" shear state of stress almost all over the area of the panel composite facings and very high strength values. Hence, its applicability as a reliable apparatus for satisfactorily defining the inplane shear response and strength allowables of high performance composite laminates was categorically verified.

(b) The immediate conclusion of (a) is a preference for shear panels rather than shear tubes, usually assumed to display a "pure" shear state of stress, for investigating the objectives of a test program such as the present one. In spite of the complexity involved in manufacturing the panels and the tedious procedure of preparing them for testing, the shear tubes were not found to be even an equivalent competitor. It is very difficult to manufacture a tube which will meet the design specifications, especially the required wall thickness. Usually they are observed to be considerably thicker. Also more efforts are required in their manufacturing process than for the panels. Nevertheless, the tubes display very poor response, in particular low strength allowables.

(c) Pronounced strengthening "core effect" was recognized in the "weak" in-shear laminate configurations. This effect should be considered and accounted for in reducing the test data to obtain the shear response corresponding to such laminates. The method of determining the "core effect" ehich was proposed in [2] and was only strudied and evaluated on the experimental data obtained for a particular core should be further extended to different core types and sizes to verify the method of [2].

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APPENDIX A

The advantageous application of advanced composites isn't categorically advocated unless there exists, among other requirements, ample knowledge and physical insight into their response and performance under cyclic loading, and their loading and unloading characteristics. Though the present test program wasn't aimed at studying the influence of the abovementioned loading procedure, an attempt was made to gather such kind of information during the course of the test program for many of the shear tubes. These tubes were gradually torqued and unloaded in a cyclic manner and the results achieved from this test procedure are presented in Figs. APA1 through APA6.

Figs. APA1I and APA1II present the results of cycling tests on two [±15°] GR/E tubes. No significant effect of this loading procedure on either one of the specimens is observed.

Loading and unloading effects on three [±30°] GR/E tubes are shown in Figs. APA2I through APA2III. These figures reveal that only the tube of Fig. APA2I was unaffected by this loading procedure. However, one may observe that the initial recorded strains are unreliable as long as the shell is "settling" itself in the first stages of loading and that with further loading of the specimen the responses of all cycles are very much alike. Hence it might be concluded that loading and unloading have had almost no effect on the behavior of this type of laminate configuration.

Fig. APA3 presents the results of a cycling test on a [±45°] GR/E tube. It appears from this figure that load cycling slightly influenced the performance of the laminate, where the modulus increased insignificantly with each new cycle.

In Figs. APA4I and APA4II loading and unloading effects on two [0°/90°]GR/E tubes are shown. It is observed that the loading procedure has had an appreciable influence on the performance of the laminate once the tube was considerably loaded in a preceding cycle. It is seen from both figures that the first low load cycles have had

no effect on the tubes whereas the last cycle was accompanied by an appreciable reduction of the laminate modulus.

Figs. APA5I and APA5II present the results of cycling tests on two [0°/±45°/90°] GR/E tubes. Neither of these tubes exhibits any influence on its response due to this loading procedure.

The influence of loading and unloading on the response of a [0°/90°] B/E tube is shown in Fig. APA6. It appears from this figure that each cycle is followed by a noticeable decrease in the stiffness (modulus) of the tube.

TABLE 1 Shear Panels - Test Results

1" (inch) = 2.540×10^{-2} metre (m)
1 pound force = 4.448222 Newton(N)
1 kip = 10^3 pound force
1 psi = 6.894757×10^3 Pascal(Pa)
1 ksi = 10^3 psi

Laminate Construction	GRAPHITE-EPOXY(3M SP-286T3)					BORON-EPOXY(AVCO 5505/5.6 MIL.)				
	t" * meas. thick.	$P_{TEN.} + \lvert P_{COMP.} \rvert$ (kips)	No "core effect" $\tau_{ULT.}$ (kips)	Gxy (best fit) $\times 10^6$psi	$\gamma_{max.}$ $\times 10^{-3}$	t" * meas. thick.	$P_{ten.} + \lvert P_{comp.} \rvert$ (kips)	No "core effect" $\tau_{ULT.}$ (kips)	Gxy (best fit) $\times 10^6$psi	$\gamma_{max.}$ $\times 10^{-3}$
[0°]	.046 .045** .039	8.08 9.83 7.29	8.87 11.03 9.57	.90 (.57)	-	.054 .052	10.03 8.70	9.38 8.44	.93 (.66)	27.5
[±15°]	.044 .044	23.71 21.64	27.21 24.84	1.71 (1.38)	17.3	.052 .053	44.88 37.22	43.59 35.47	2.97 (2.70)	15.5
[±30°]	.045 .044 .043	26.85 29.53 30.28	30.14 33.90 35.56	3.47 (3.14)	9.2	.053 .053	59.80 55.32	56.99 52.72	6.46 (6.19)	8.5
[±45°]	.044 .044	38.46 26.76	44.15 30.72	4.42 (4.09)	10.2	.052 .052	74.38 84.11	72.25 81.70	8.37 (8.10)	10.02
[0°/90°]	.045 .044	15.65 15.80	17.56 18.14	.93 (.60)	90.0	.053 .054	11.78 12.25	11.23 11.46	.87 (.60)	42.5
[0°/±45°/90°]	.044 .045	27.37 24.42	31.41 27.41	2.74 (2.41)	12.0	.054 .053	51.96 56.91	48.60 54.23	4.63 (4.36)	11.0

* Laminate nominal thickness: Graphite-Epoxy - 8x.0052=.0416"
Boron-Epoxy - 8x.0067=.0536"

( ) "Core effect" eliminated

** Damaged specimen (see Results and Discussion)

TABLE 2 Shear Tubes - Dimensions and Test Results

Laminate Construction	Geometry: t" nom. (No. of plies x ply thick.)	t" meas. thick.	L" (Fig. 1B)	O.D." (Fig. 1B)	Ultimate Load & Strength: $M_{ULT.}$ (klb-in)	(τ_{ULT}) nom. (ksi)	(τ_{ULT}) meas. (ksi)	(Gxy) nom. (best fit) $x10^6$ psi	γ_{xy} $x10^{-3}$	Loading & Unloading Procedure: M_I (klb-in)	Gxy_I $x10^6$ psi	M_{II} (klb-in)	Gxy_{II} $x10^6$ psi	M_{III} (klb-in)	Gxy_{III} $x10^6$ psi	M_{IV} (klb-in)	Gxy_{IV} $x10^6$ psi
GRAPHITE-EPOXY LAMINATES (3M SP-286T3)																	
$[\pm 15°]_{4S}$	.083	.104	6.01	3.004	35.83	32.61	26.03	2.25									
		.101	6.00	3.003	31.27	28.40	23.34	(1.82)	16.	10.49	2.36	20.12	2.22	31.27	2.32		
		.102	5.98	3.024	31.05	27.82	22.64			10.59	2.06	20.35	2.10	31.05	2.02		
$[\pm 30°]_{4S}$	.083	.113	6.00	3.018	40.68	36.88	27.09	4.91		+25.48	5.35	-25.39	4.69	-40.68	4.74		
		.110	6.00	3.027	43.26	38.90	29.35	(3.68)	7.7	10.33	5.05	43.26	5.06				
		.109	6.00	3.025	32.12	28.90	22.01			-25.05		-30.03		+32.12			
$[\pm 45°]_{4S}$	.083	.120	6.00	3.030	45.72	41.31	28.57	6.28									
		.122	6.00	3.042	60.04	53.88	36.66	(4.31)	-								
		.121	5.98	3.041	53.78	48.26	33.10			-30.72	5.69	+30.99	5.74	-53.78	5.86		
$[90°]_{8T}$	.042	.065	6.00	3.027	6.18	10.68	6.90	.94									
		.060	6.00	3.010	7.10	12.37	8.66	(.64)	22.								
		.060	6.00	3.034	7.07	12.12	8.48										
$[0°/90°]_{2S}$	.042	.045	6.17	3.032	6.06	10.29	9.60	.60									
		.048	6.16	3.163	6.02	9.40	8.23	(.55)	35.	1.25	70	2.14	.70	6.02	.61		
		.046	6.16	3.024	6.29	10.75	9.82										
		.043	6.18	3.013	6.74	11.58	11.31			1.57	.80	2.08	.80	3.06	.79	6.74	.70
$[0°/\pm 45°/90°]_{2S}$	.083	.111	6.02	2.884	29.63	27.20	20.34	3.29									
		.130	6.02	2.990	41.85	39.15	25.00	(2.32)	8.6	11.53	3.42	20.31	3.47	41.85	3.43		
		.112	6.02	3.025	31.13	28.04	20.77			10.34	3.12	20.44	3.21	31.13	3.19		
BORON-EPOXY LAMINATES (AVCO 5505/5.6 MIL. DIA)																	
$[\pm 15°]_{4S}$	.107	.158	6.01	3.022	44.69	32.42	21.96	4.06									
		.156	6.01	3.030	45.24	32.59	22.35	(2.77)	10.								
		.156	6.01	3.025	54.05	39.07	26.80										
$[\pm 30°]_{3S}$	.080	.097	5.96	3.034	22.06*	20.33	16.77	10.00									
		.115	6.00	3.037	55.76	51.97	36.15	(7.21)	5.2								
		.121	6.01	3.037	50.92	47.65	31.50										
$[\pm 45°]_{3S}$	.080	.132	5.96	3.055	22.09*	20.56	12.46	13.30									
		.134	5.99	3.038	26.74*	25.23	15.06	(7.94)	4.1								
		.136	6.00	3.054	48.22	45.07	26.51										
$[90°]_{8T}$	.054	.075	6.00	3.037	5.16	6.93	4.99	1.07									
		.082	6.00	3.042	6.39	8.60	5.66	(.73)	14.								
		.079	5.98	3.038	6.19	8.33	5.69										
$[0°/90°]_{2S}$	.054	.055	6.00	3.038	5.43	7.19	7.06	.64									
		.055	6.00	3.052	6.31	8.28	8.13	(.62)	35.	2.27	.69	4.55	.66	6.31	.63		
		.057	6.00	3.038	6.02	7.99	7.57										
$[0°/\pm 45°/90°]_{2S}$	.107	.160	6.01	3.029	42.44*	28.65	19.16	5.81									
		.169	6.00	3.028	26.85	18.25	11.55	(3.79)	5.3								
		.163	6.01	3.032	28.98	19.56	12.84										

* Tested in combined loader (NASA LRC)

( ) Moduli values corresponding to "true" measured thickness

1" (inch) = 2.540×10^{-2} metre (m)
1 pound force = 4.448222 Newton(N)
1 kip = 10^3 pound force
1 psi = 6.894757×10^3 Pascal(Pa)
1 ksi = 10^3 psi

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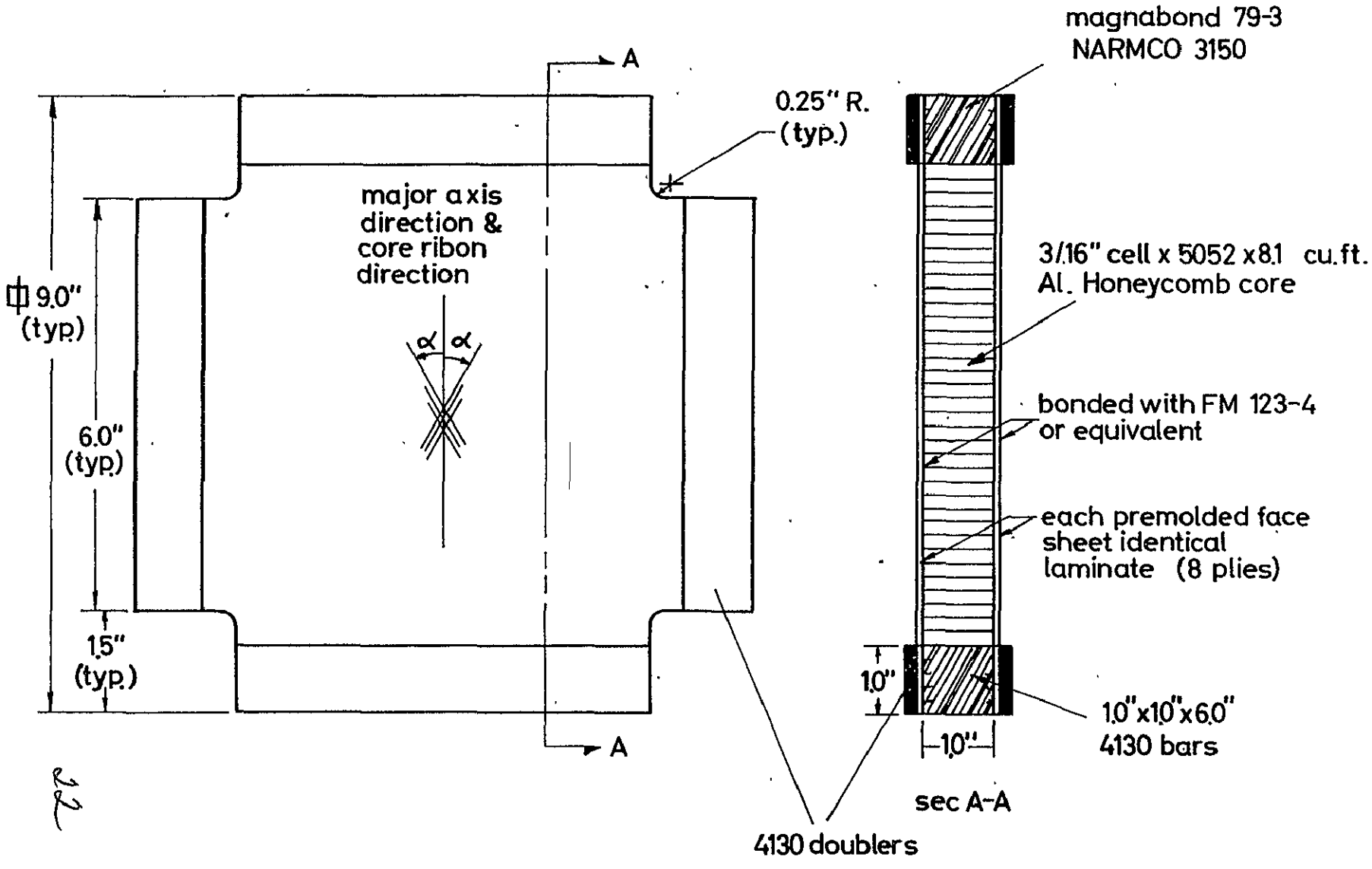
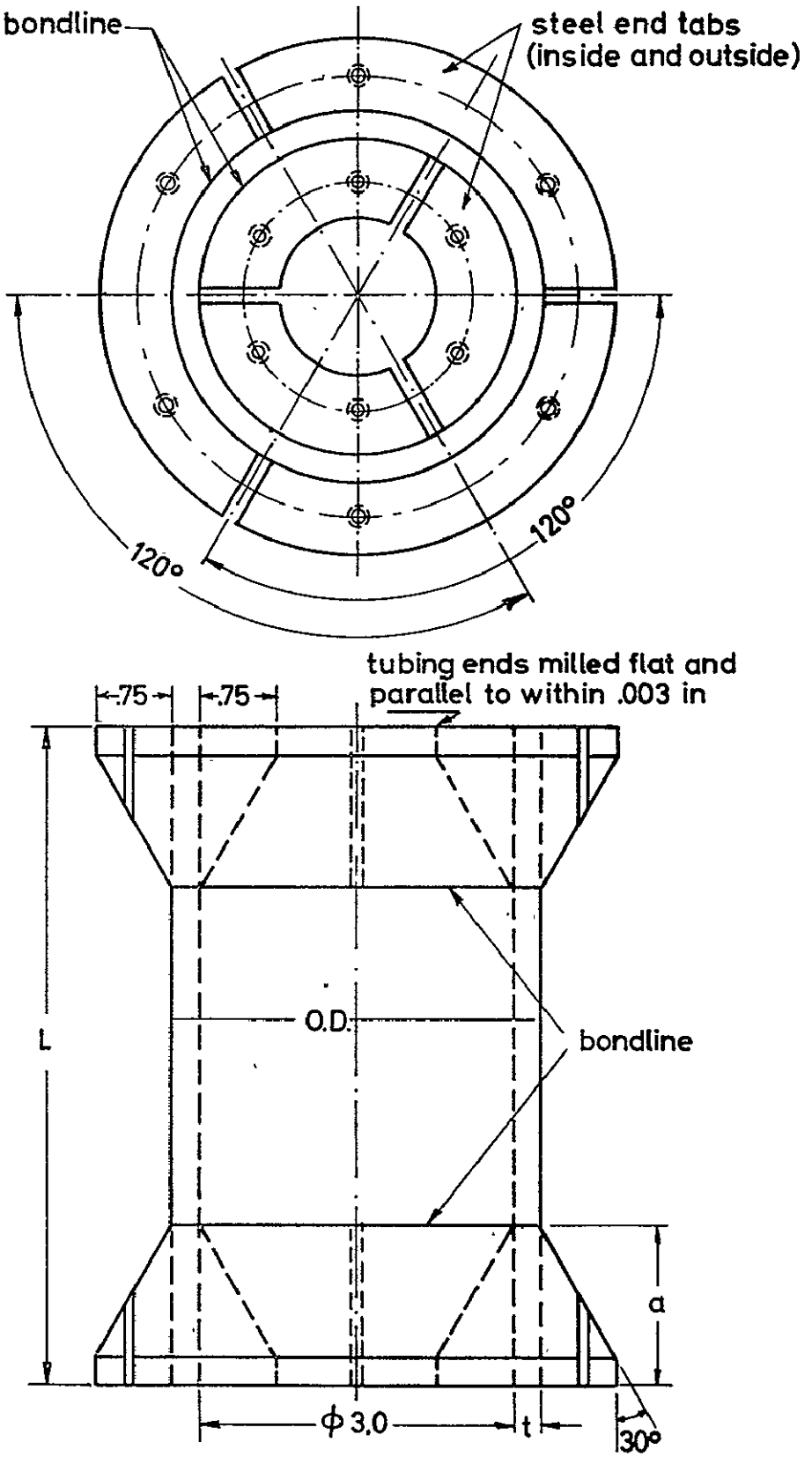


FIG. 1A SANDWICH SHEAR SPECIMEN



a–calculated to withstand ultimate load
t–number of plies x(.0052) for Graphite/Epoxy
x(.0067) for Boron/Epoxy
calculated with [12] to avoid buckling
adhesive Nitrile/Epoxy per MMH-A-132 type I
end tabs; 1010-1080 mild steel thick wall tubing

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FIG. 1B. TORSION TUBES-DIMENSIONS AND DETAILS

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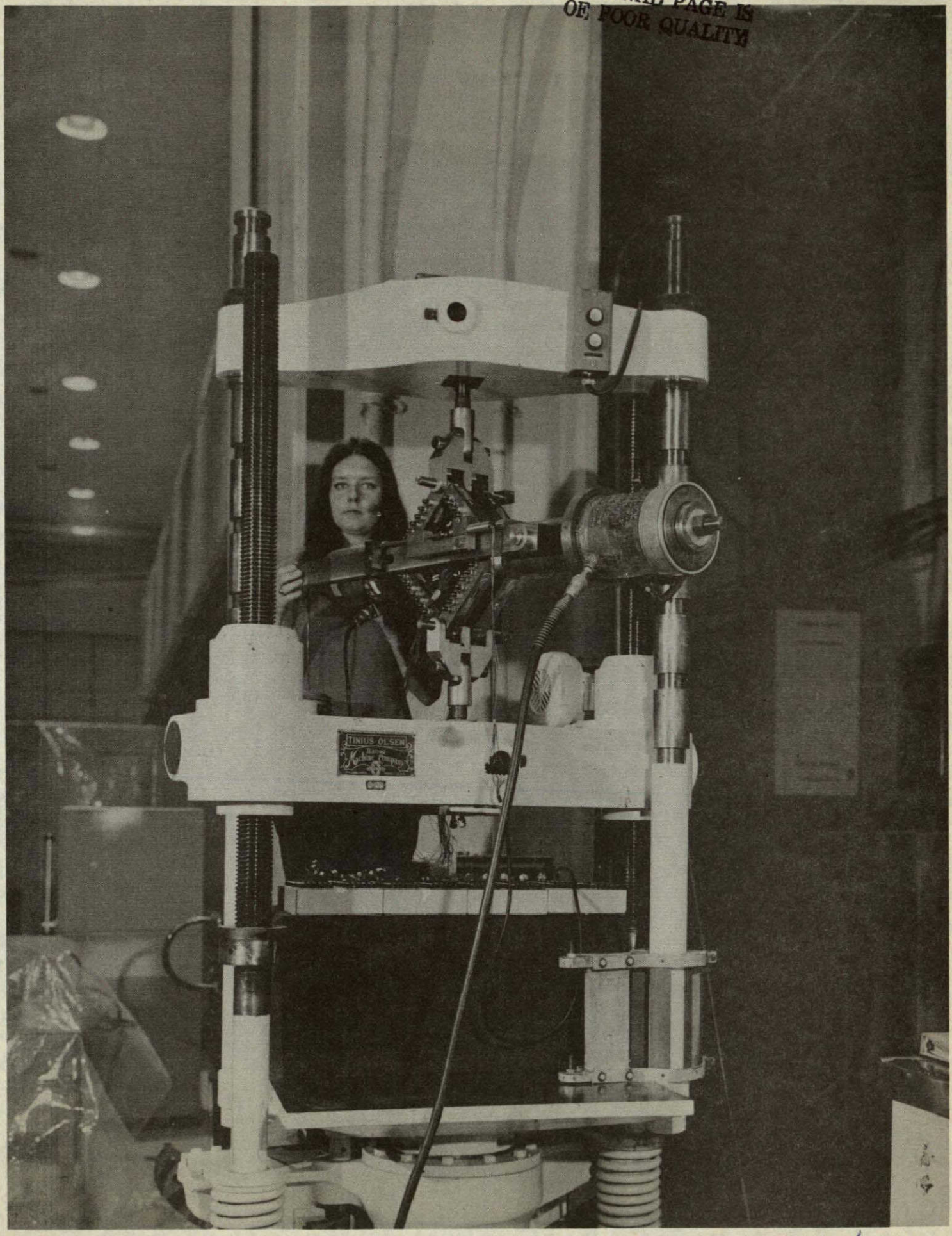

FIG. 2A TEST SET-UP FOR SHEAR PANELS

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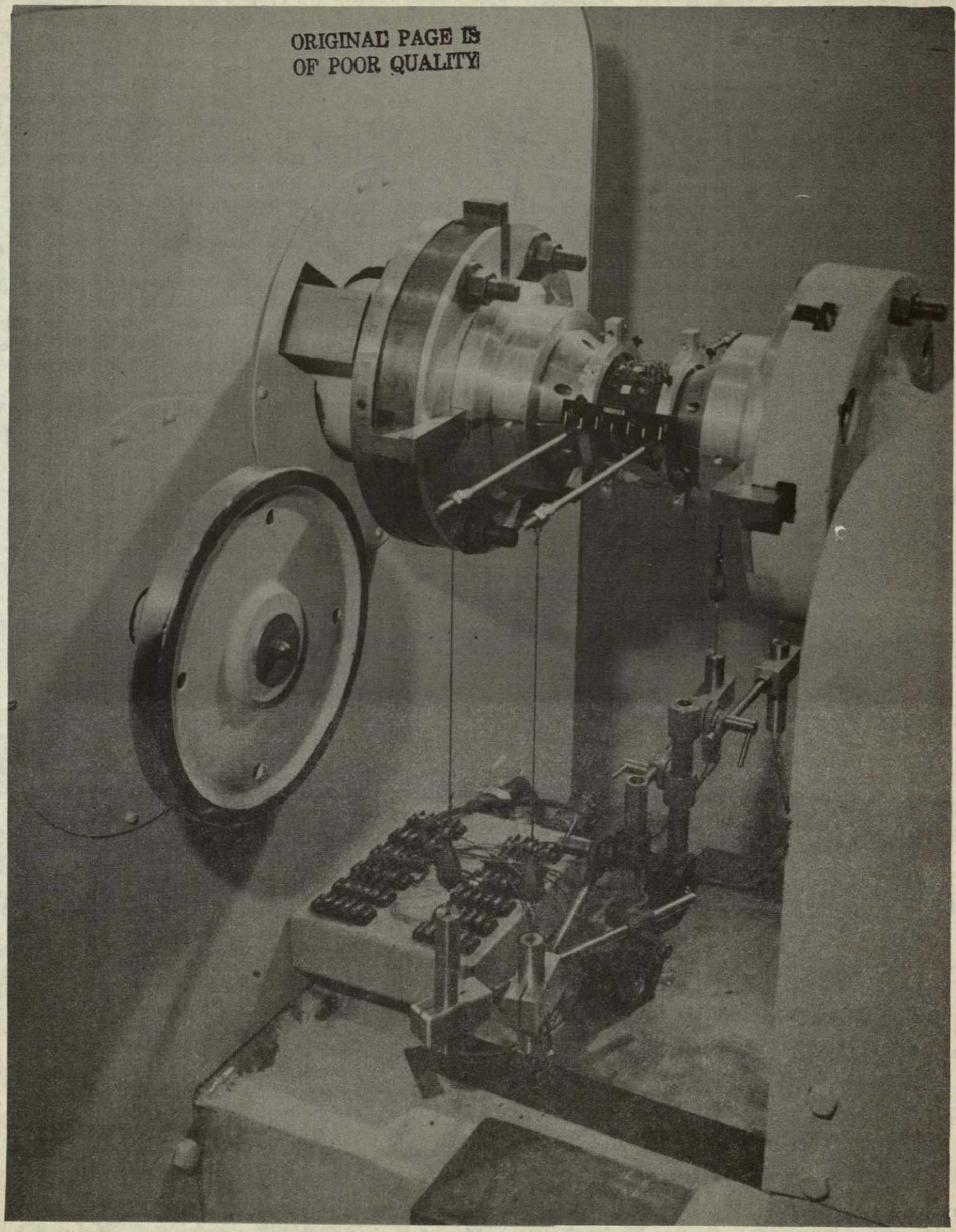

FIG. 2B TEST SET-UP FOR SHEAR TUBES

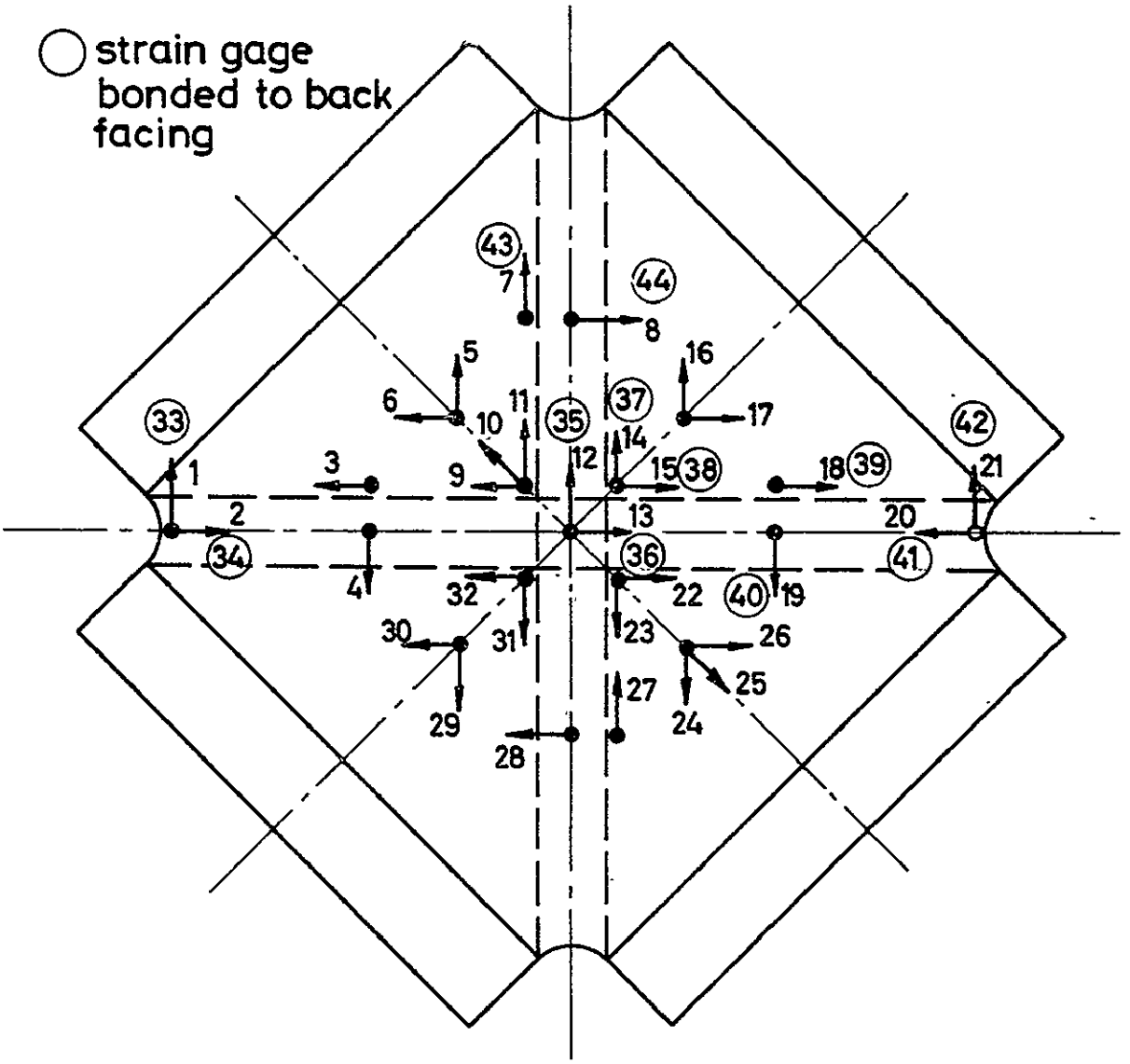

FIG. 3A SHEAR PANEL - STRAIN GAGE LOCATION
(TEST 515/RUNS 1-7)

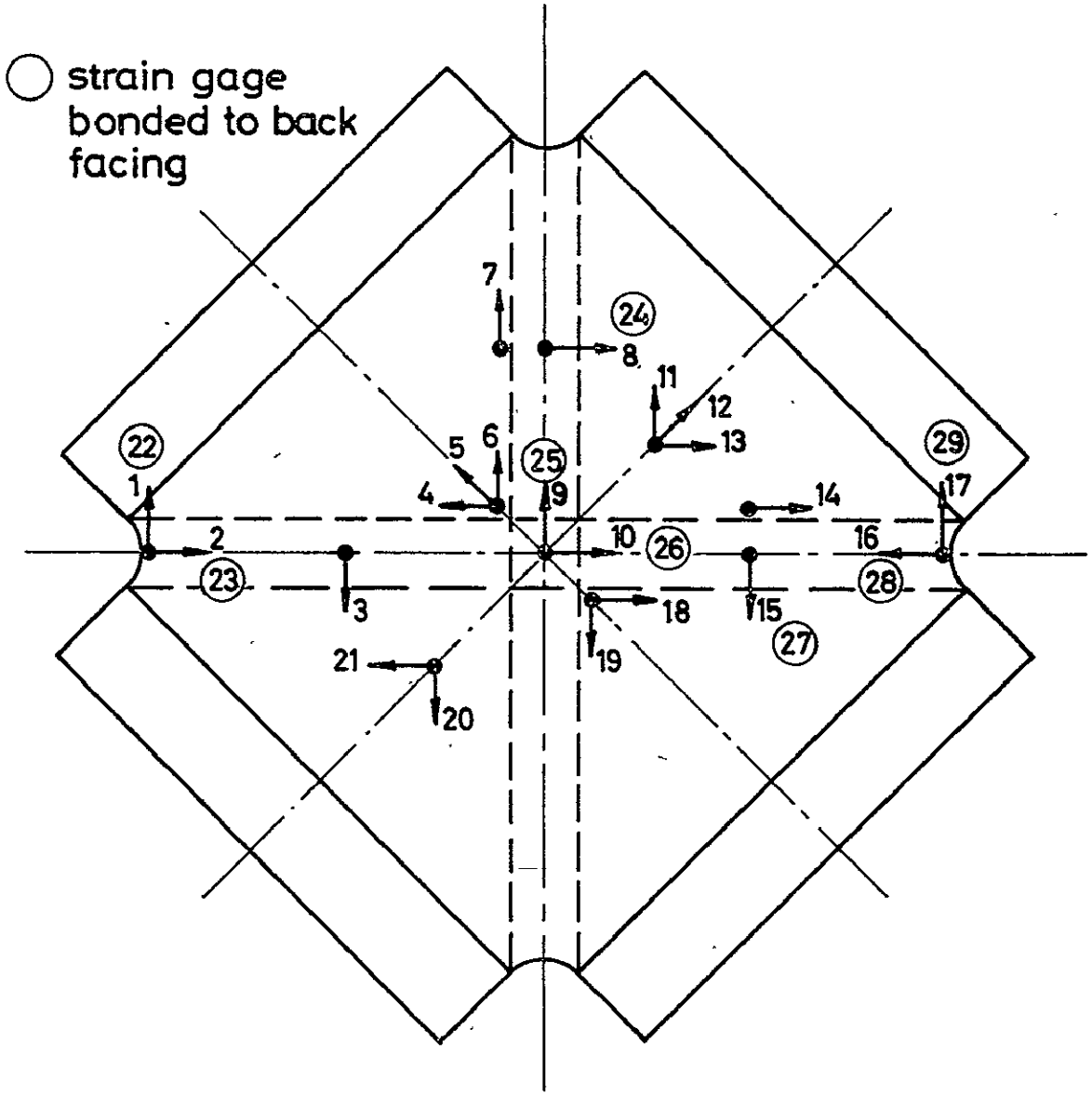

FIG. 3B SHEAR PANEL-STRAIN GAGE LOCATION
(TEST 516/RUNS 1,2,4-6 &
TEST 517/RUNS 1-10)

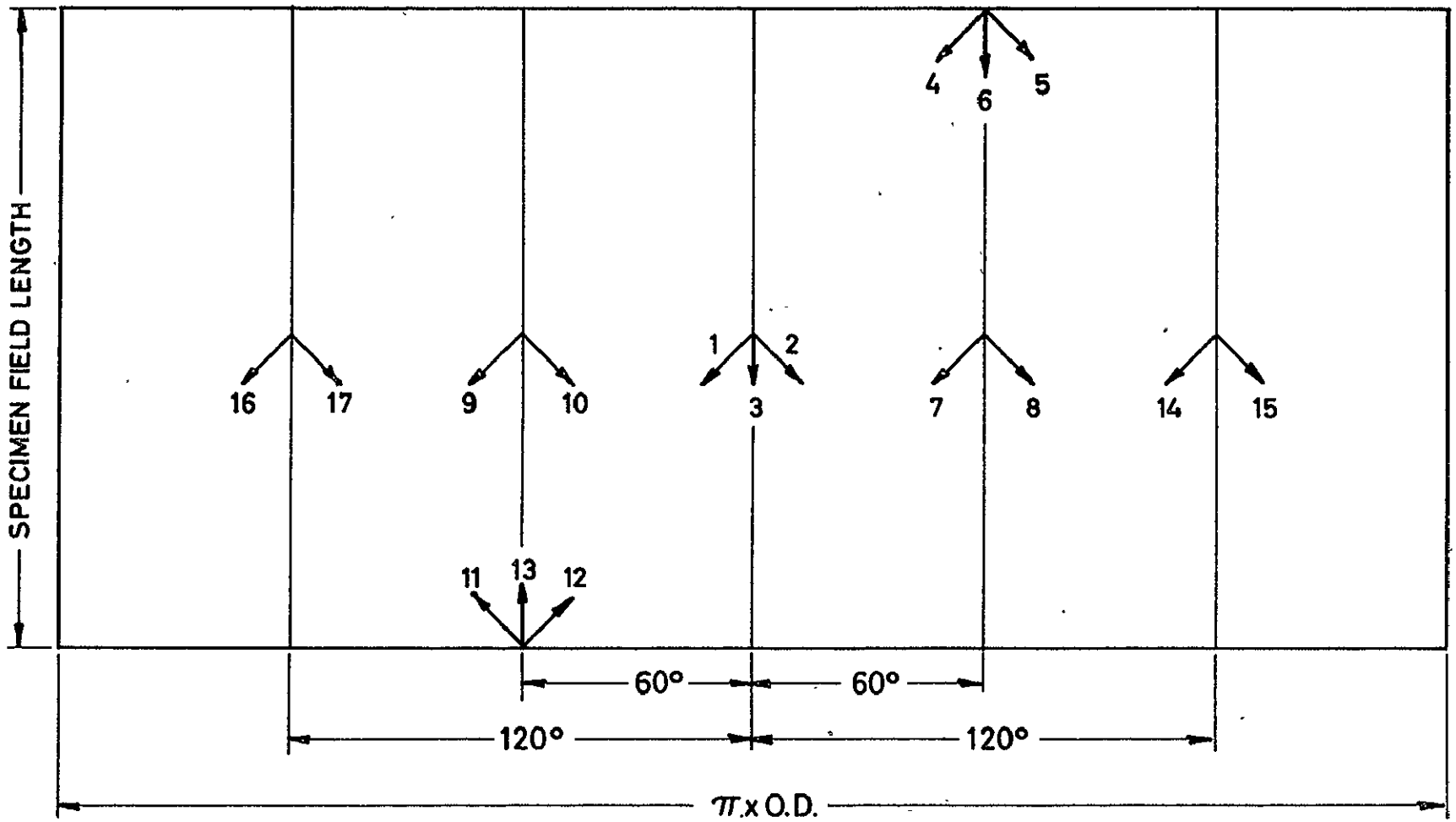

FIG. 3C TORSION TUBES-STRAIN GAGE LOCATION (DEVEL. SURFACE)

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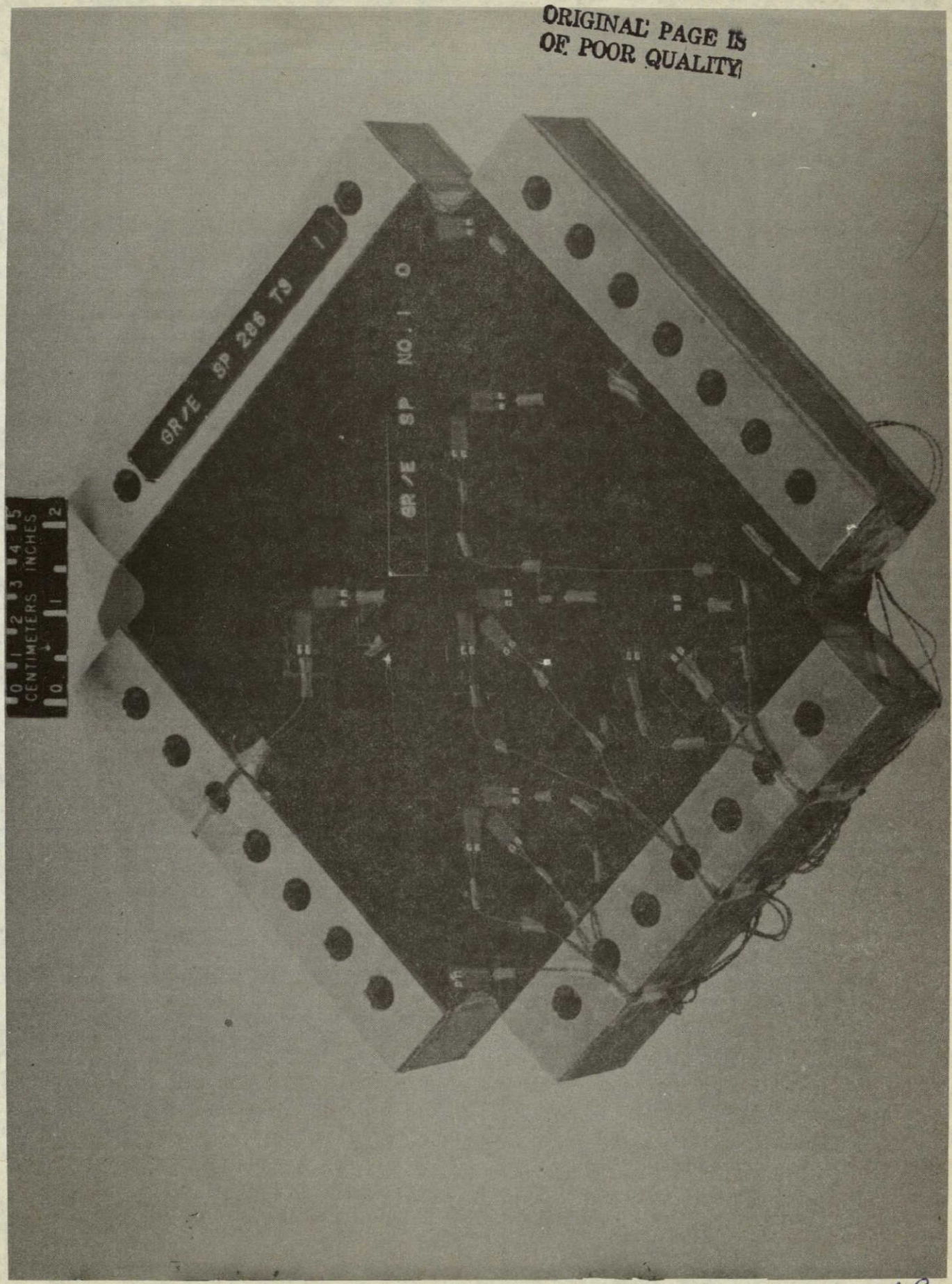

FIG. 4 SHEAR PANEL

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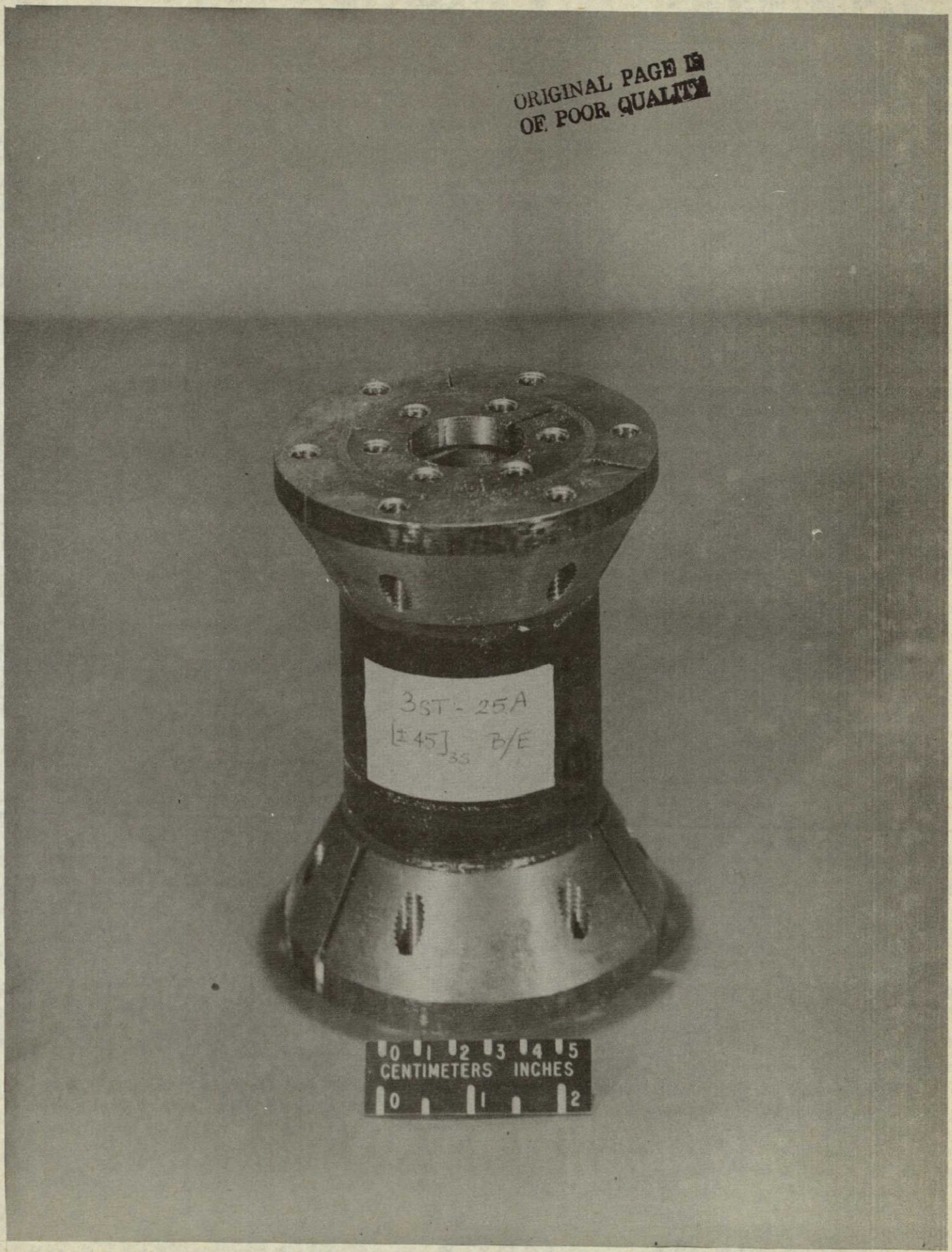


FIG. 5 SHEAR TUBE

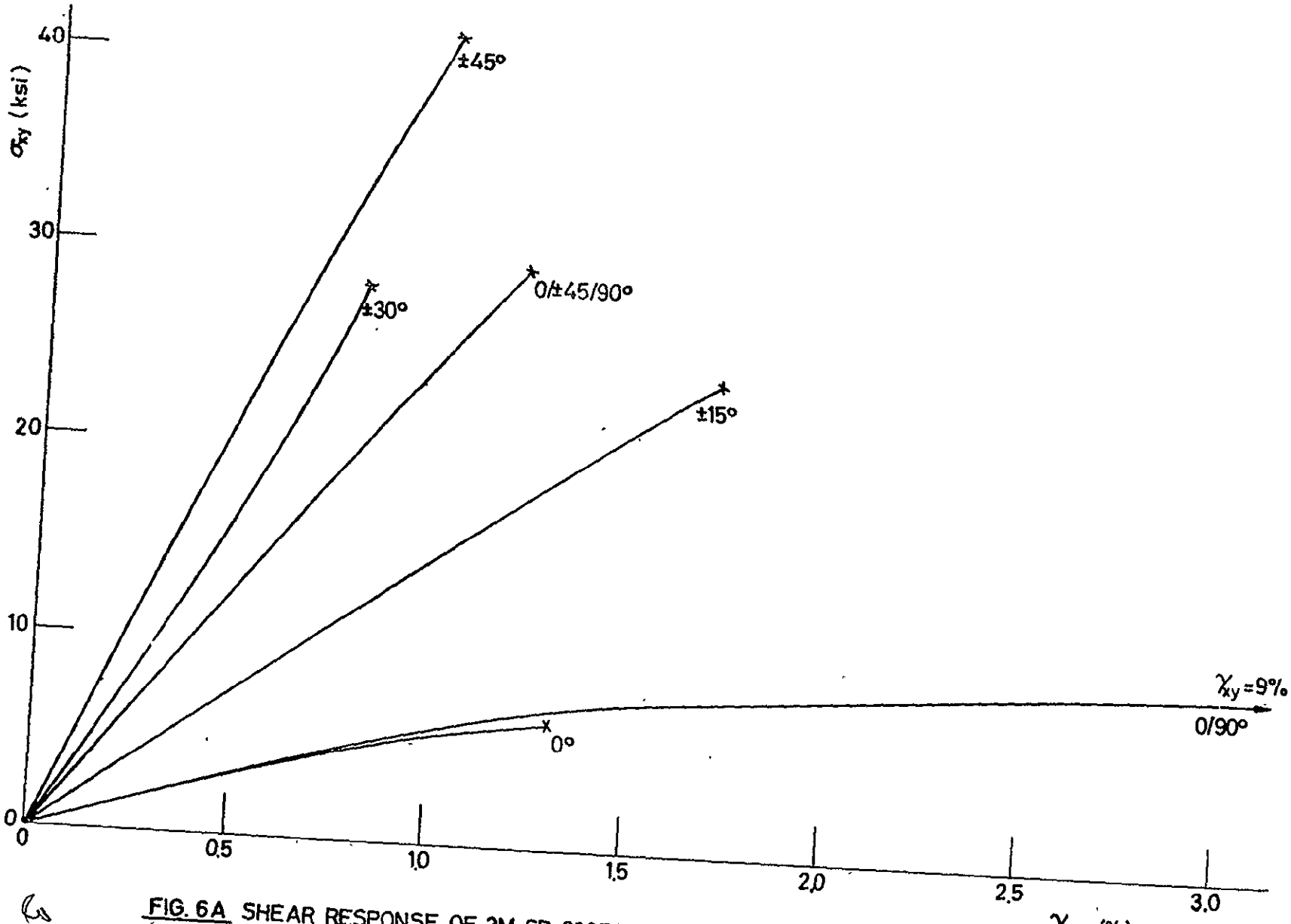


FIG. 6A SHEAR RESPONSE OF 3M SP-286T3 GRAPHITE-EPOXY SHEAR PANELS (CORRECTED)

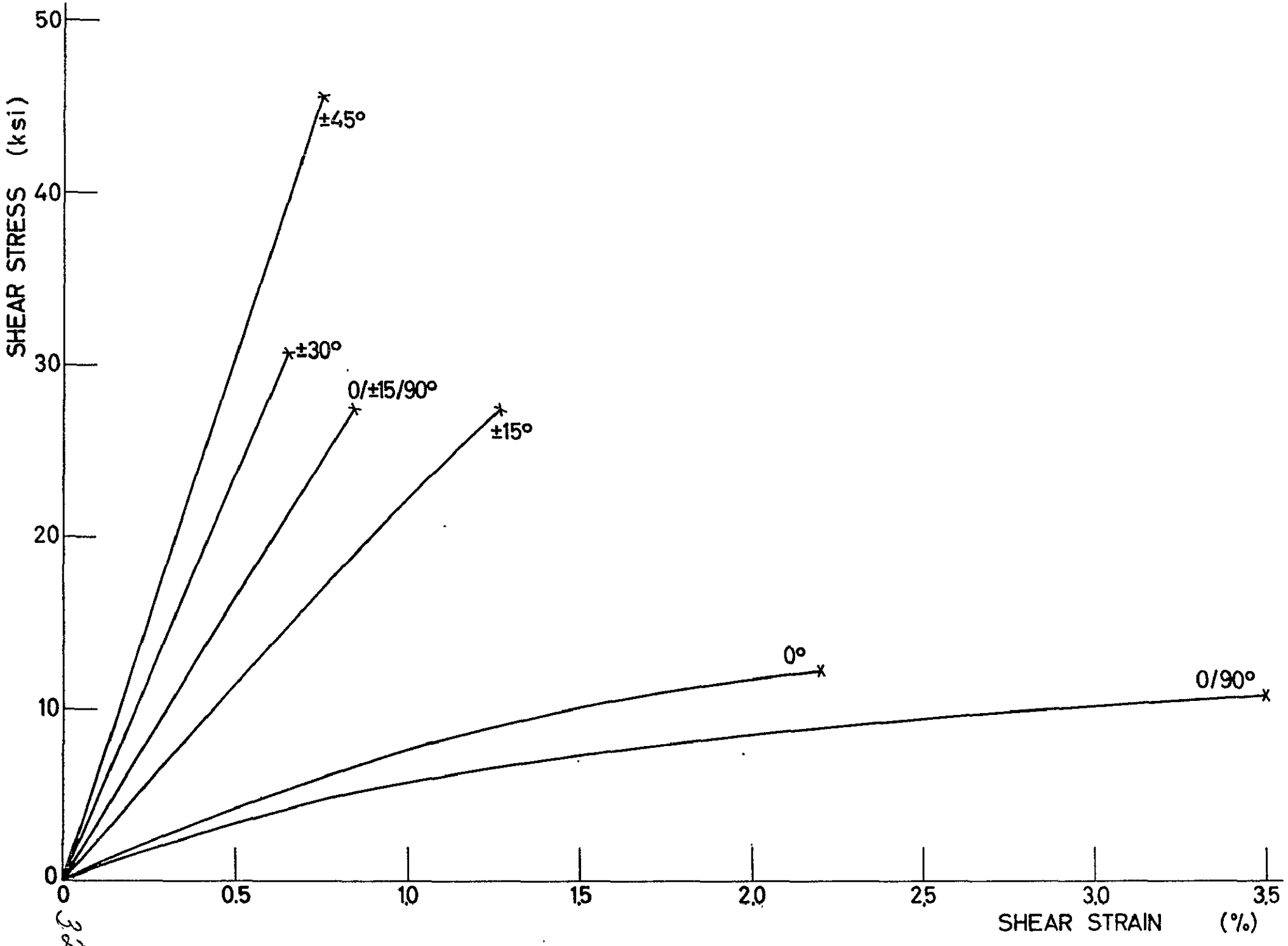


FIG. 6B SHEAR RESPONSE OF 3M SP-286T3 GRAPHITE-EPOXY SHEAR TUBES

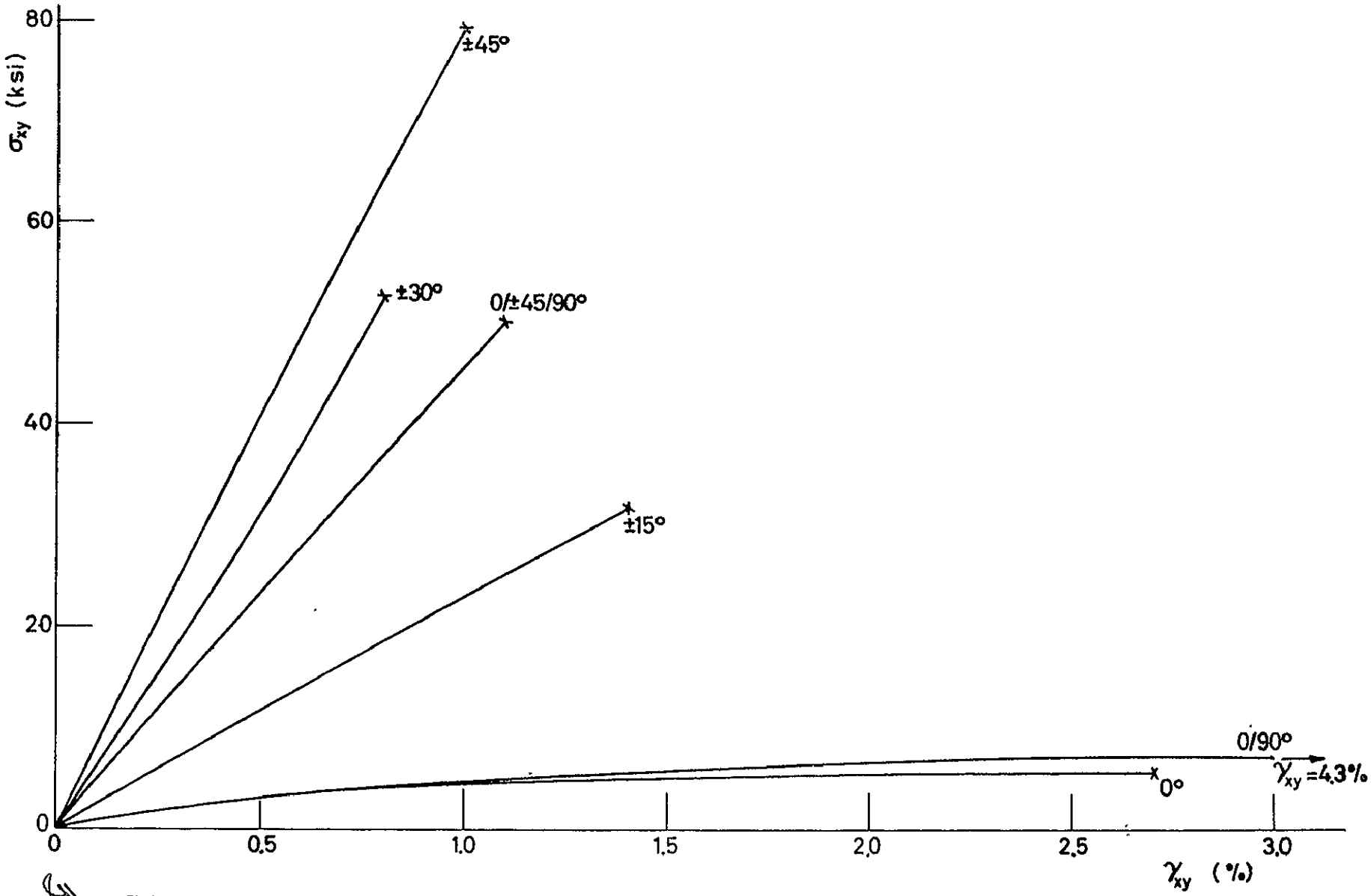


FIG. 7A SHEAR RESPONSE OF AVCO 5505/5.6 MIL. DIA. BORON-EPOXY SHEAR PANELS (CORRECTED)

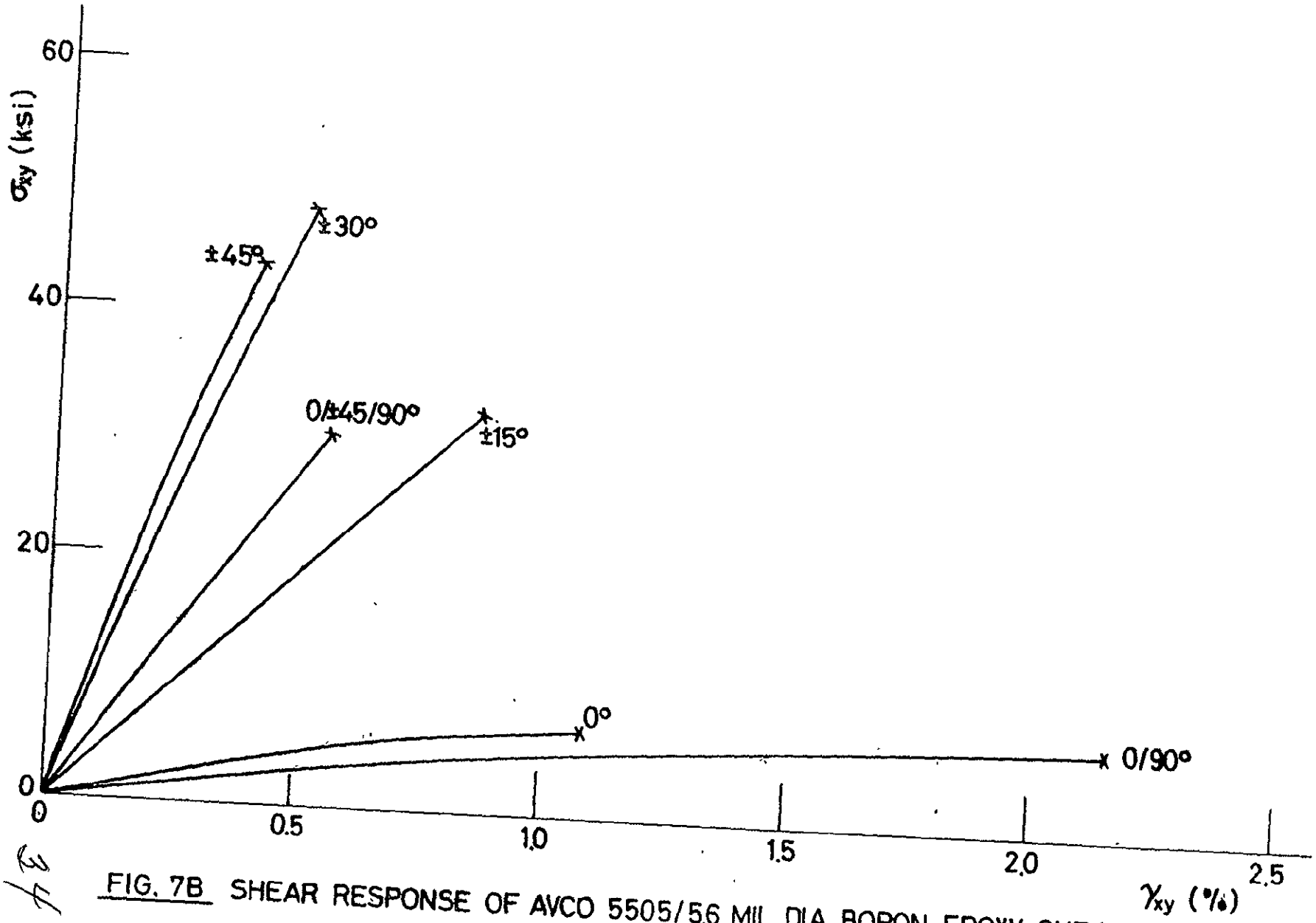
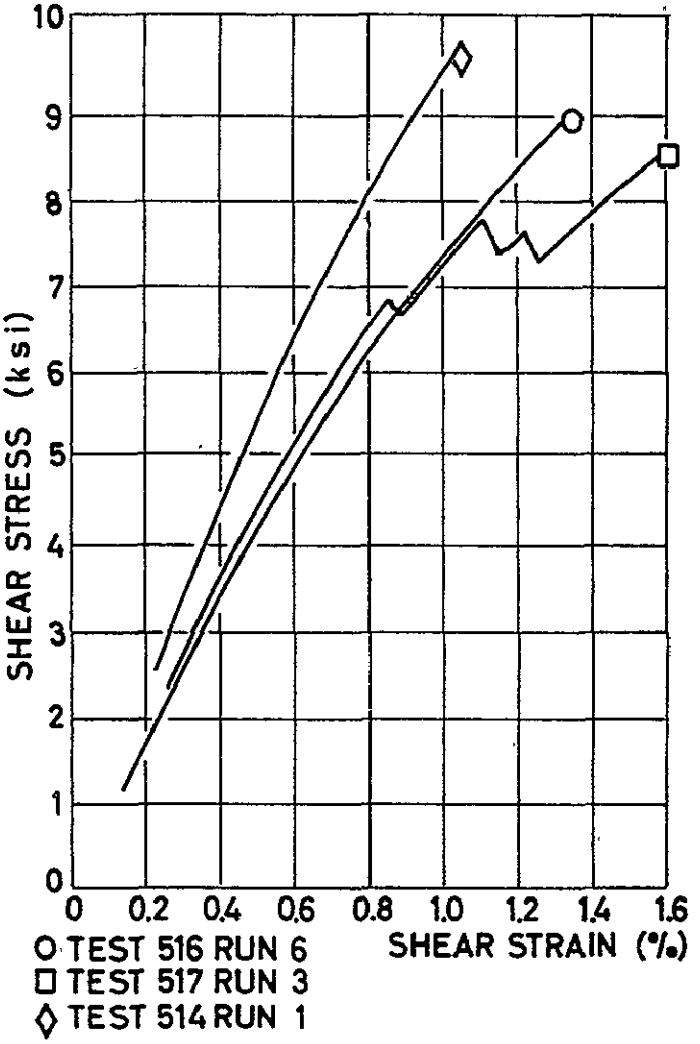


FIG. 7B SHEAR RESPONSE OF AVCO 5505/5.6 MIL DIA. BORON-EPOXY SHEAR TUBES



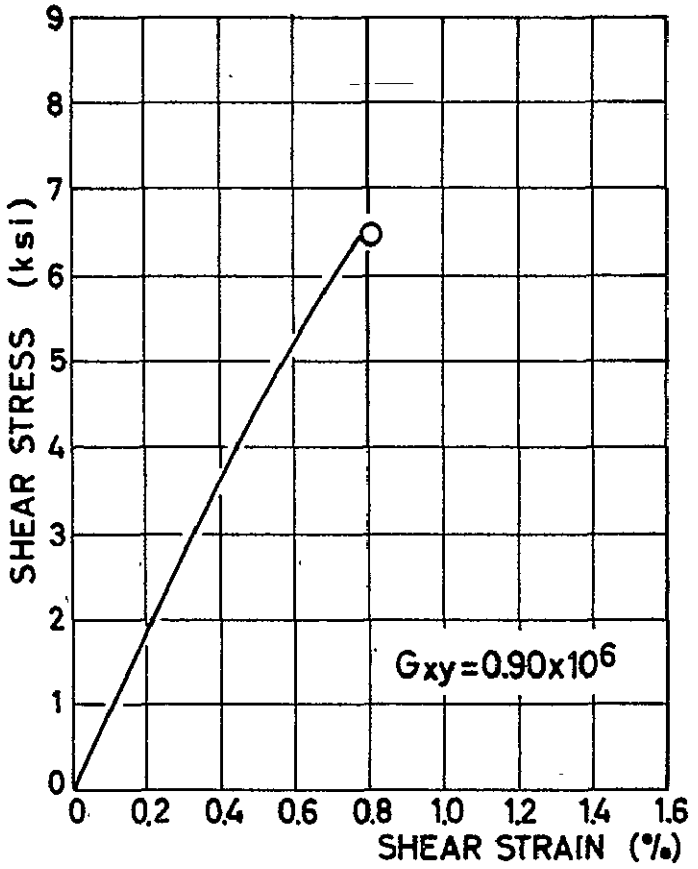
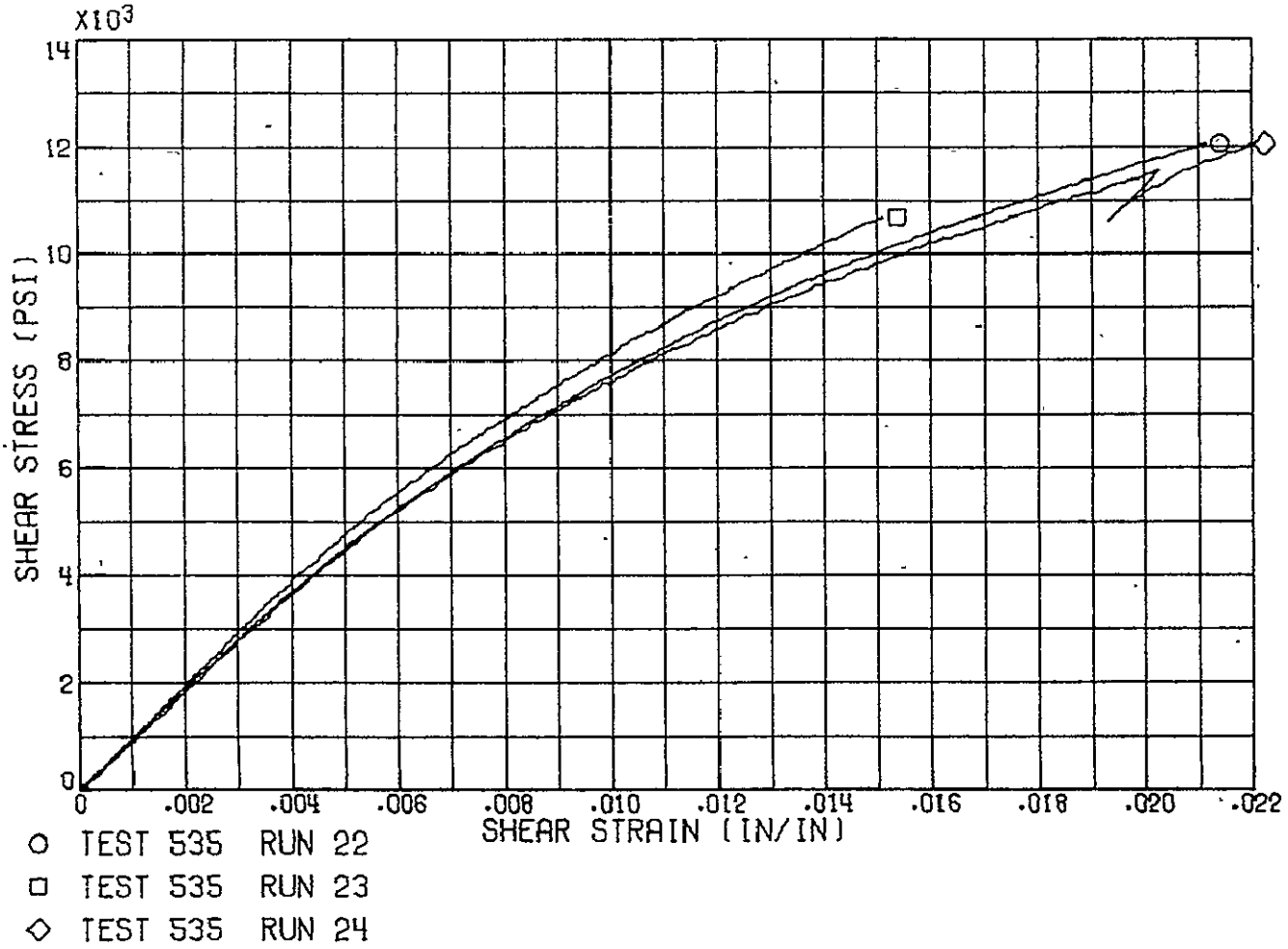


FIG. 8A SHEAR RESPONSE OF PLANAR SPECIMENS 0° GR/EP



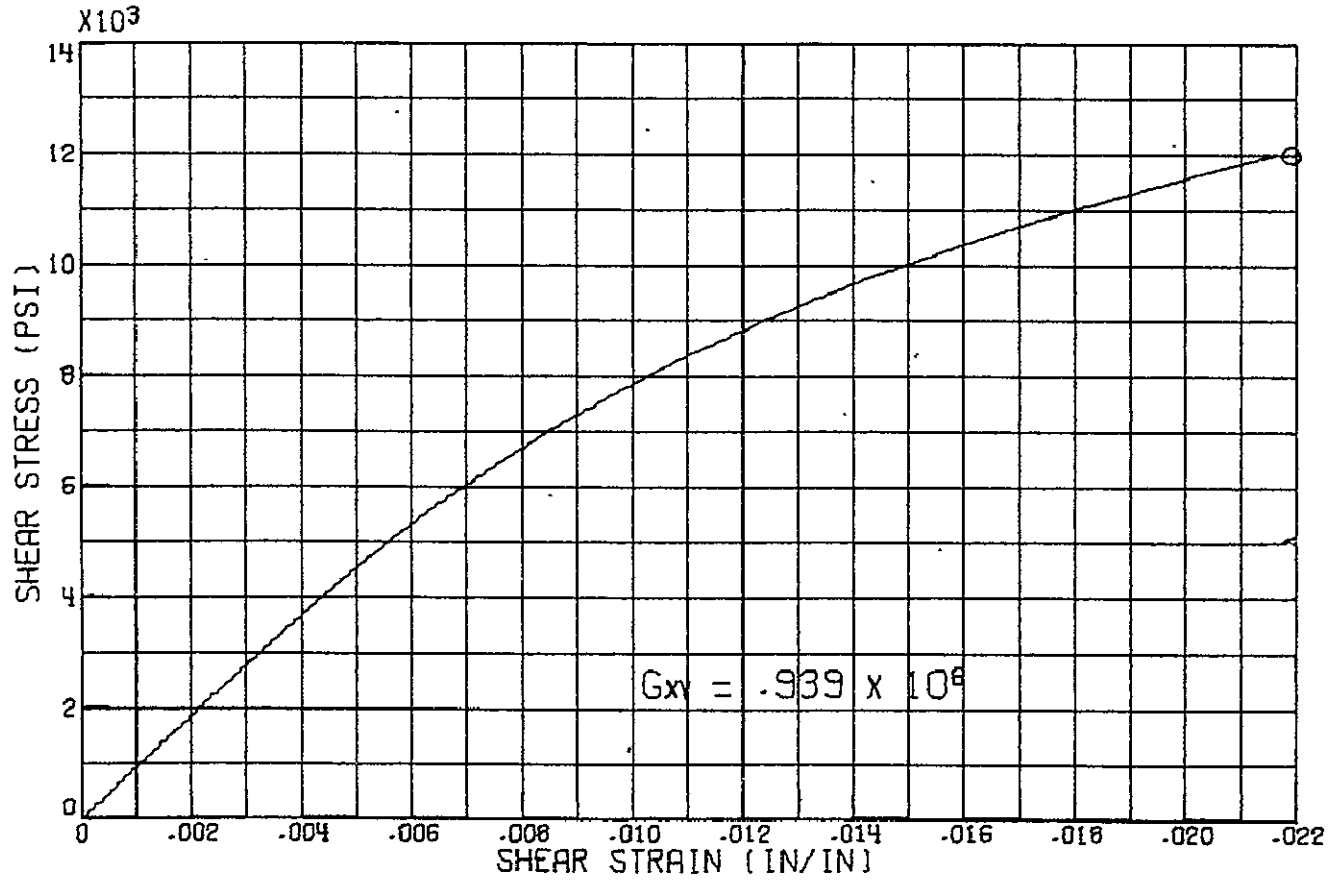


FIGURE 8B :-SHEAR RESPONSE OF TUBULAR SPECIMENS-[90]₃ GR/EP

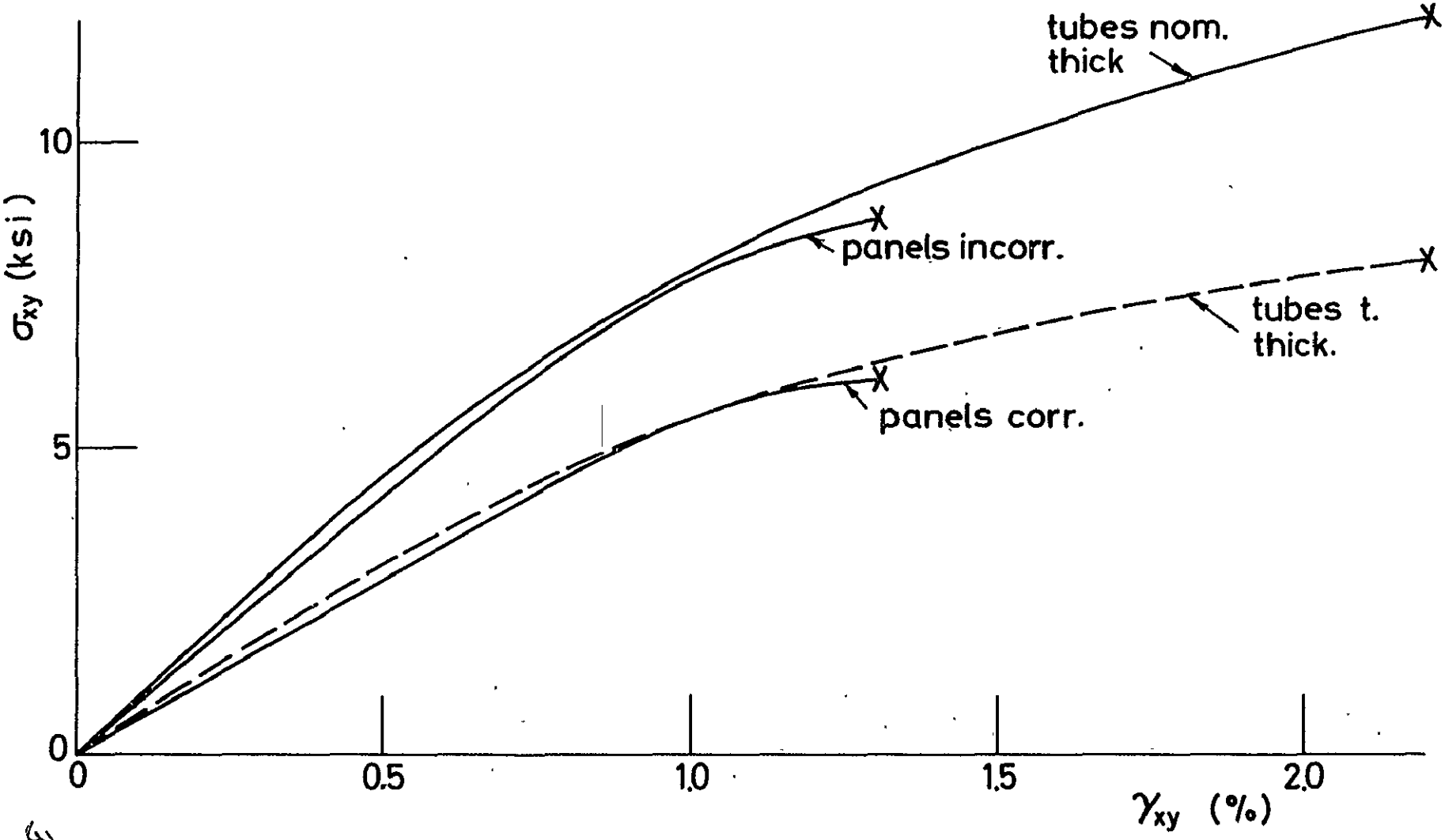
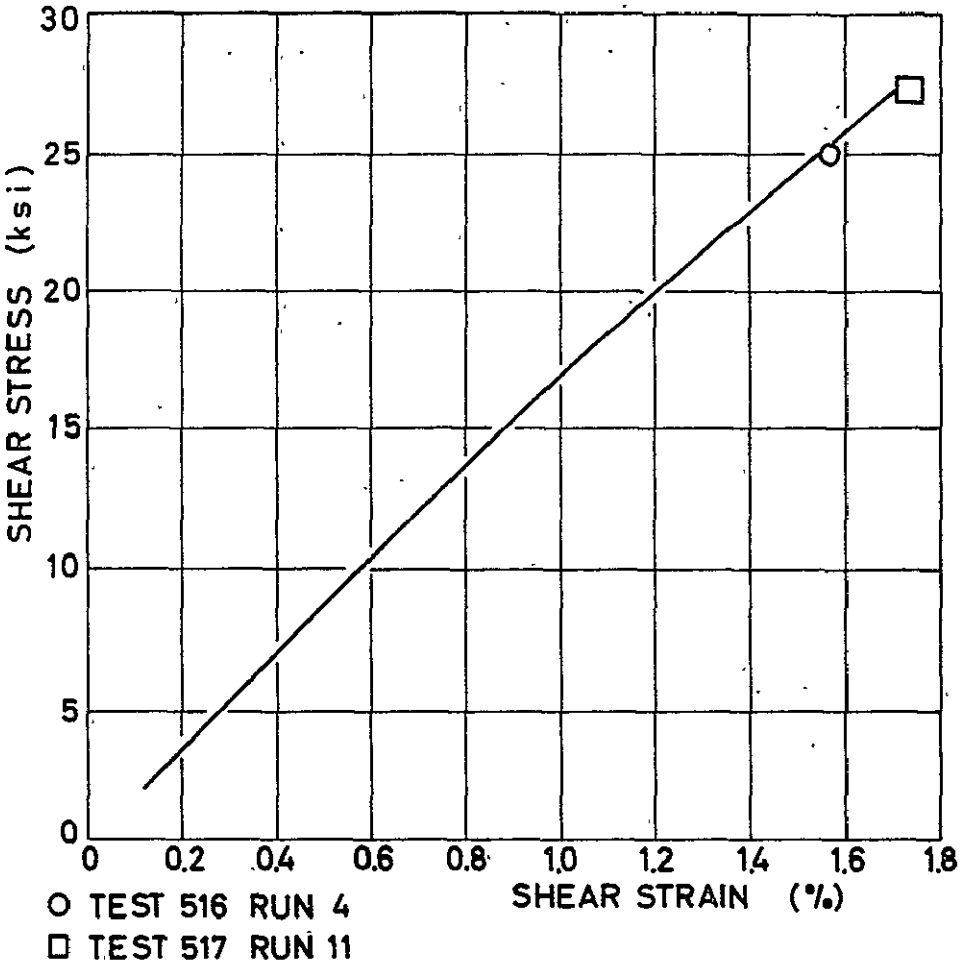


FIG. 8C SHEAR RESPONSE OF 0° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES



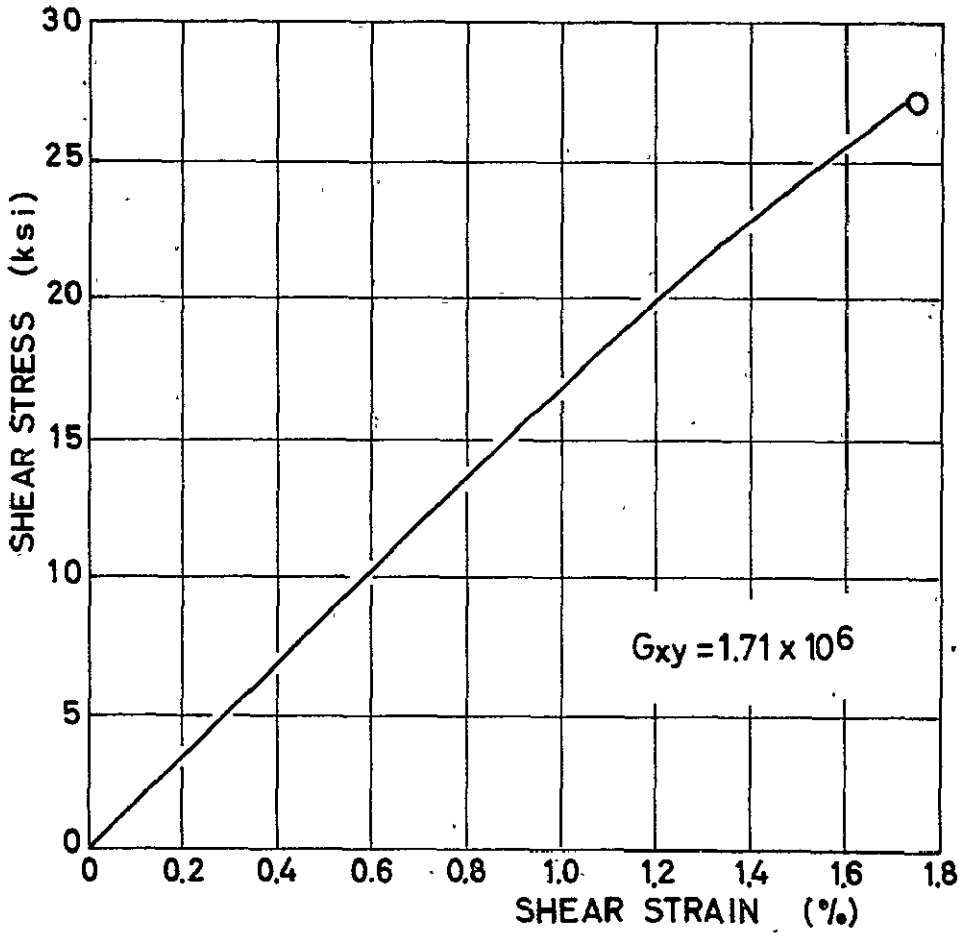
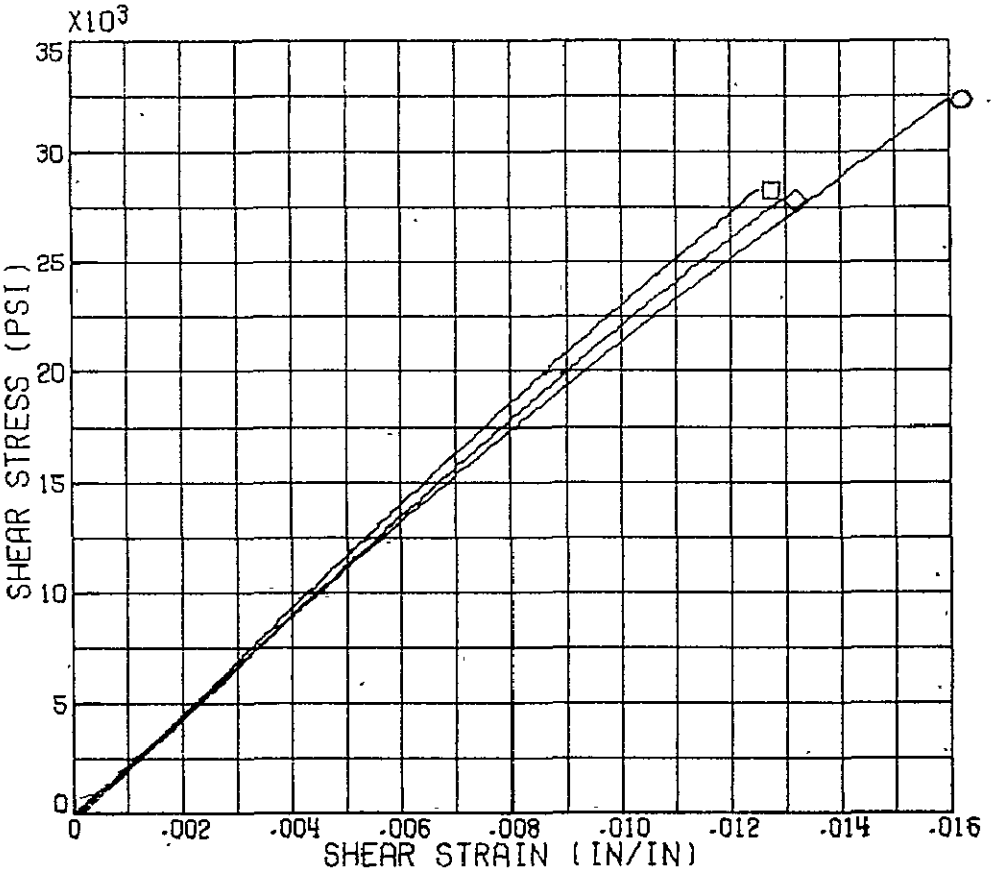


FIG. 9A SHEAR RESPONSE OF PLANAR SPECIMENS ±15° GR/EP



○ TEST 613 RUN 1
□ TEST 613 RUN 2
◇ TEST 613 RUN 3

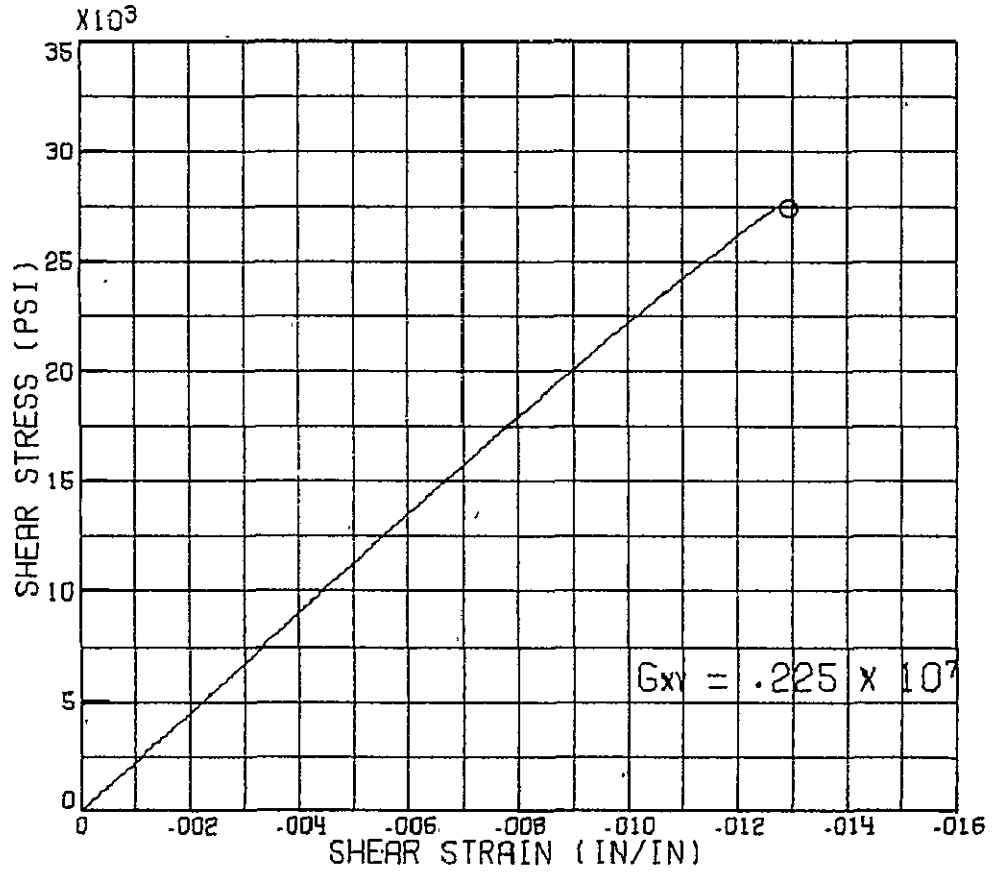


FIGURE 9B ;-SHEAR RESPONSE OF TUBULAR SPECIMENS [±15°] GR/EP

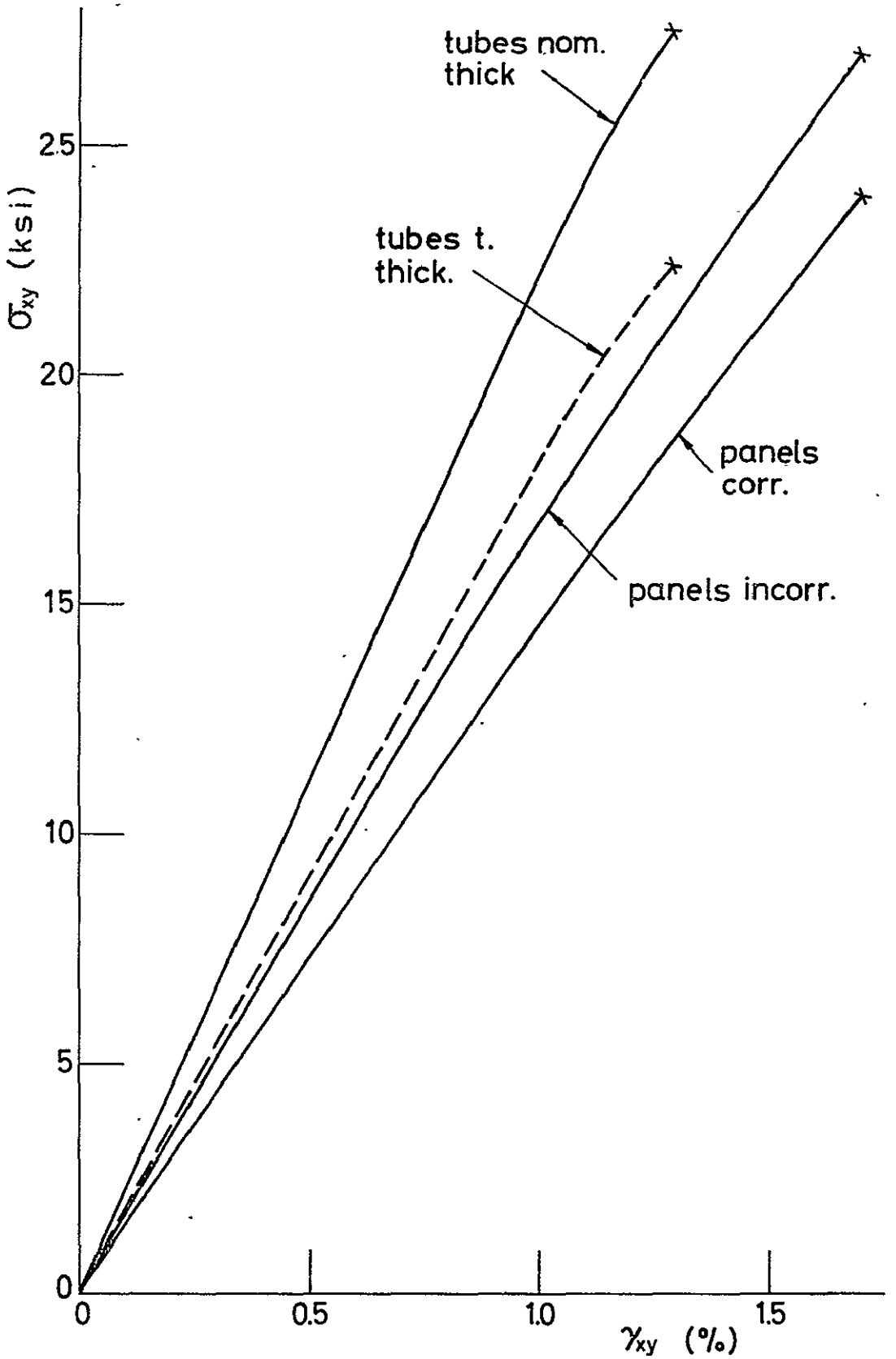
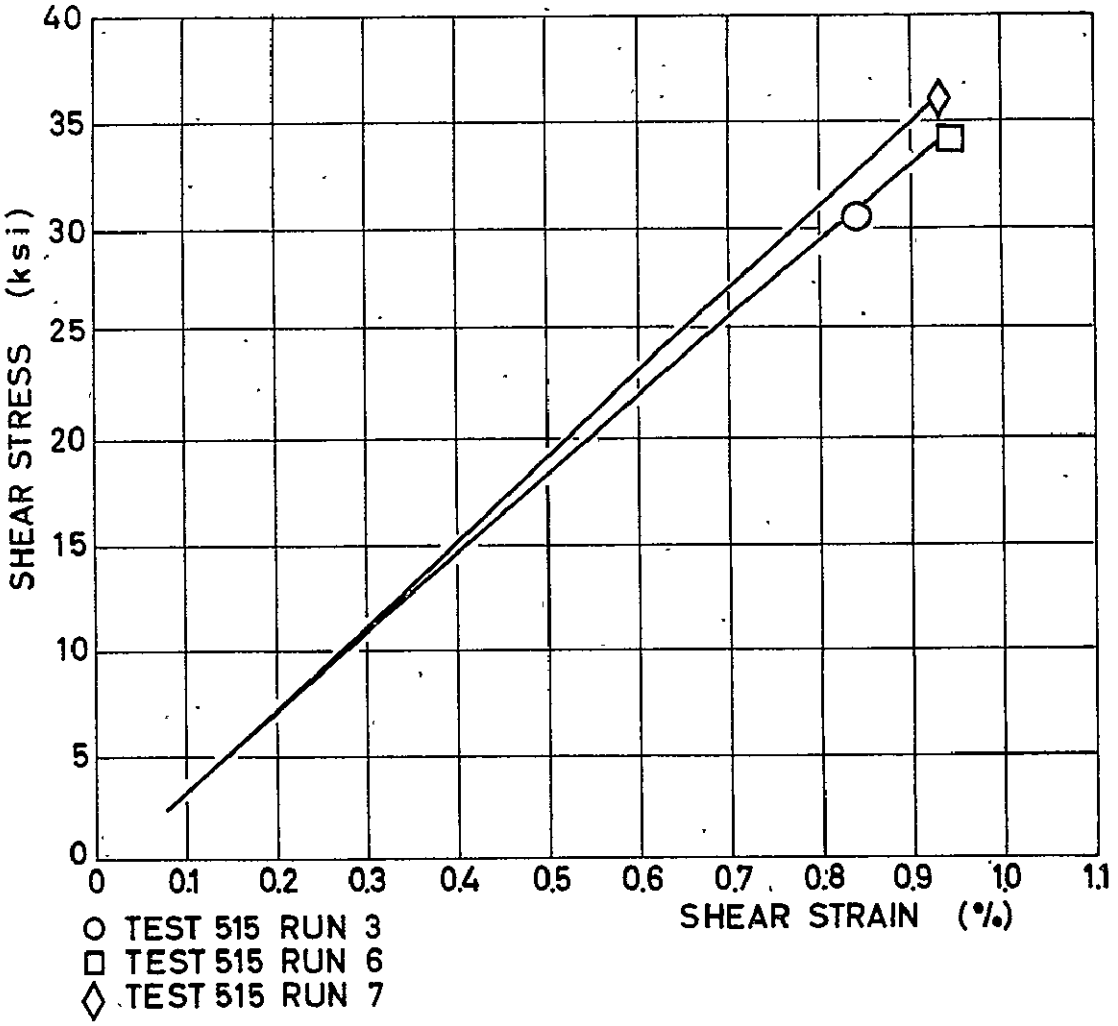


FIG. 9C SHEAR RESPONSE OF ±15° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES



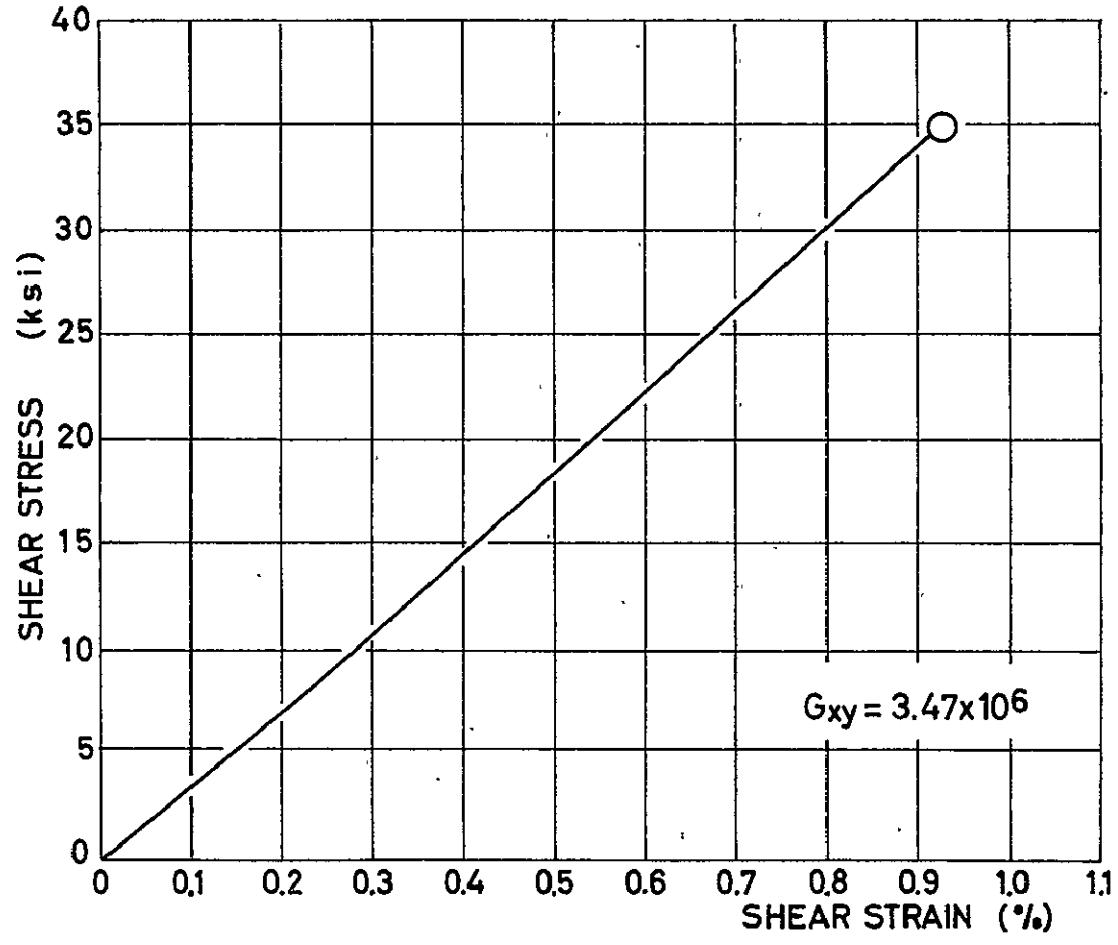
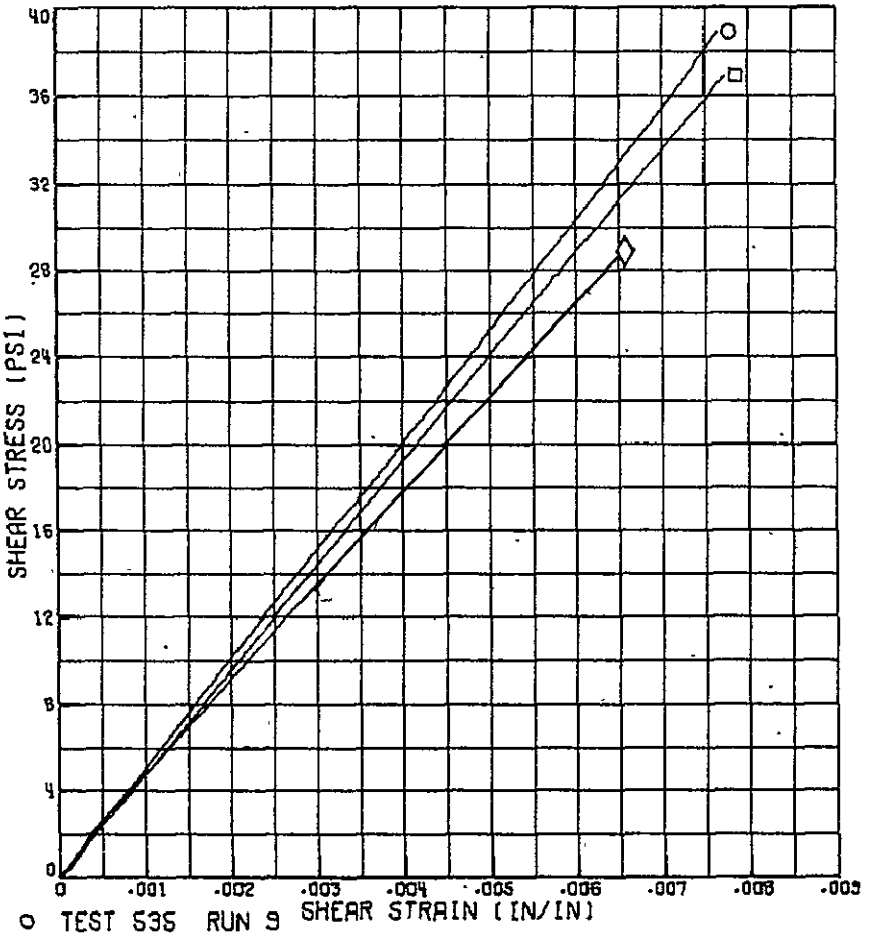
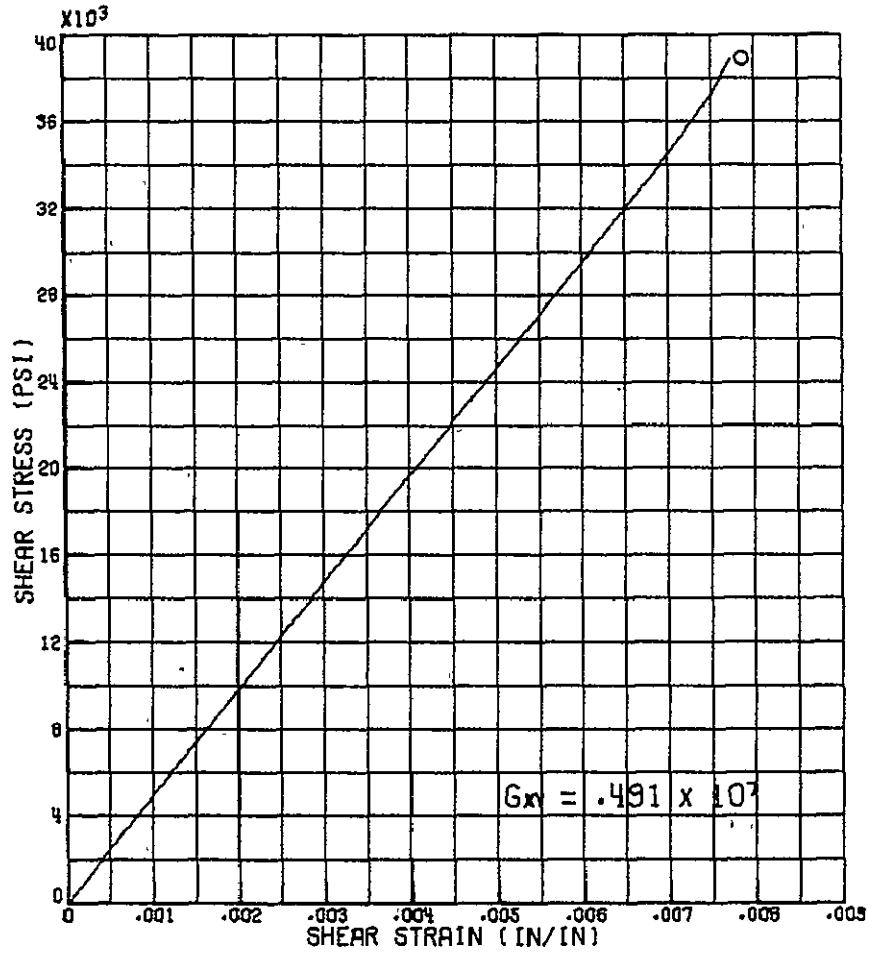


FIG. 10A SHEAR RESPONSE OF PLANAR SPECIMENS ±30° GR/EP



○ TEST 535 RUN 9
□ TEST 535 RUN 10
◇ TEST 535 RUN 13



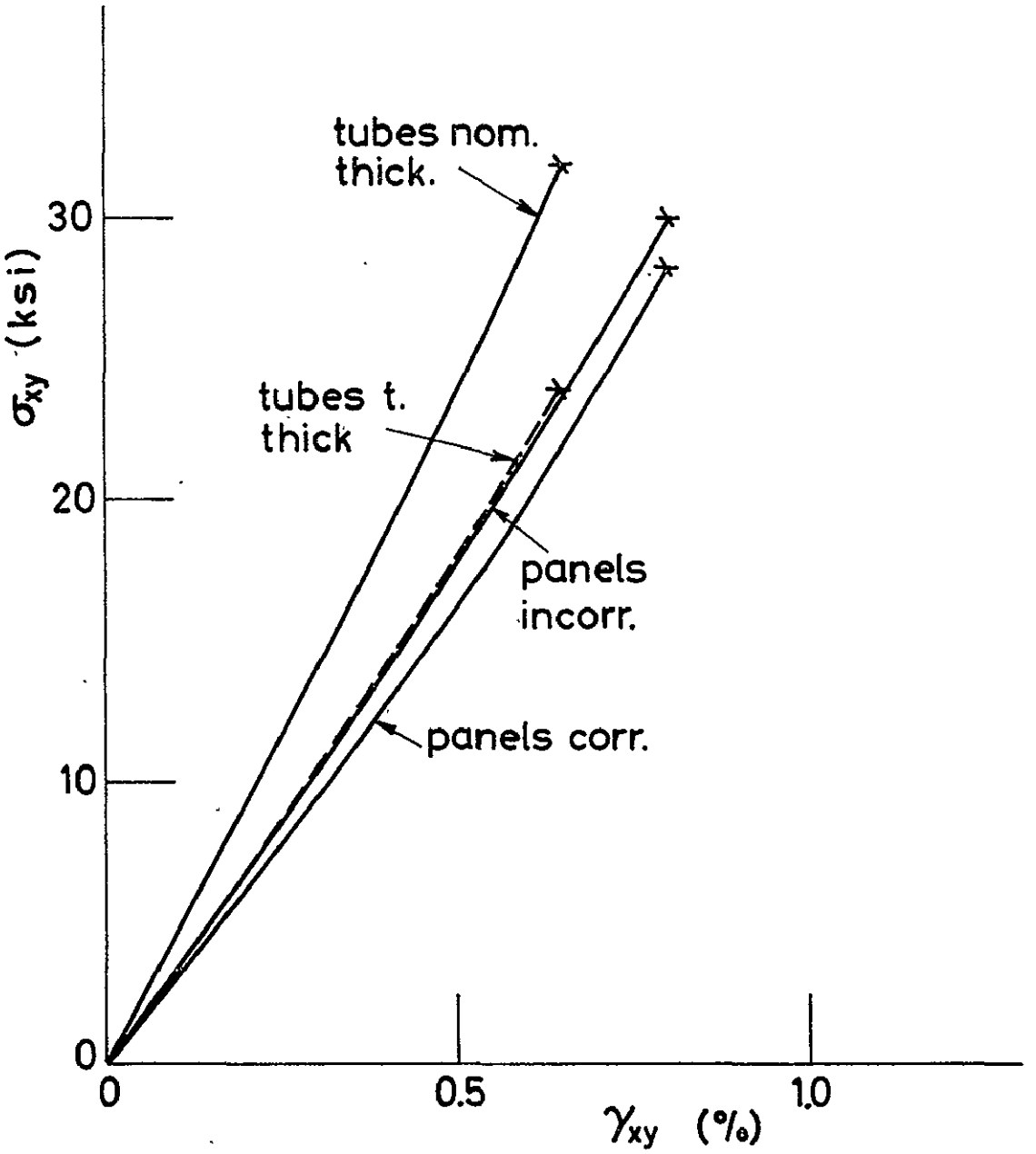
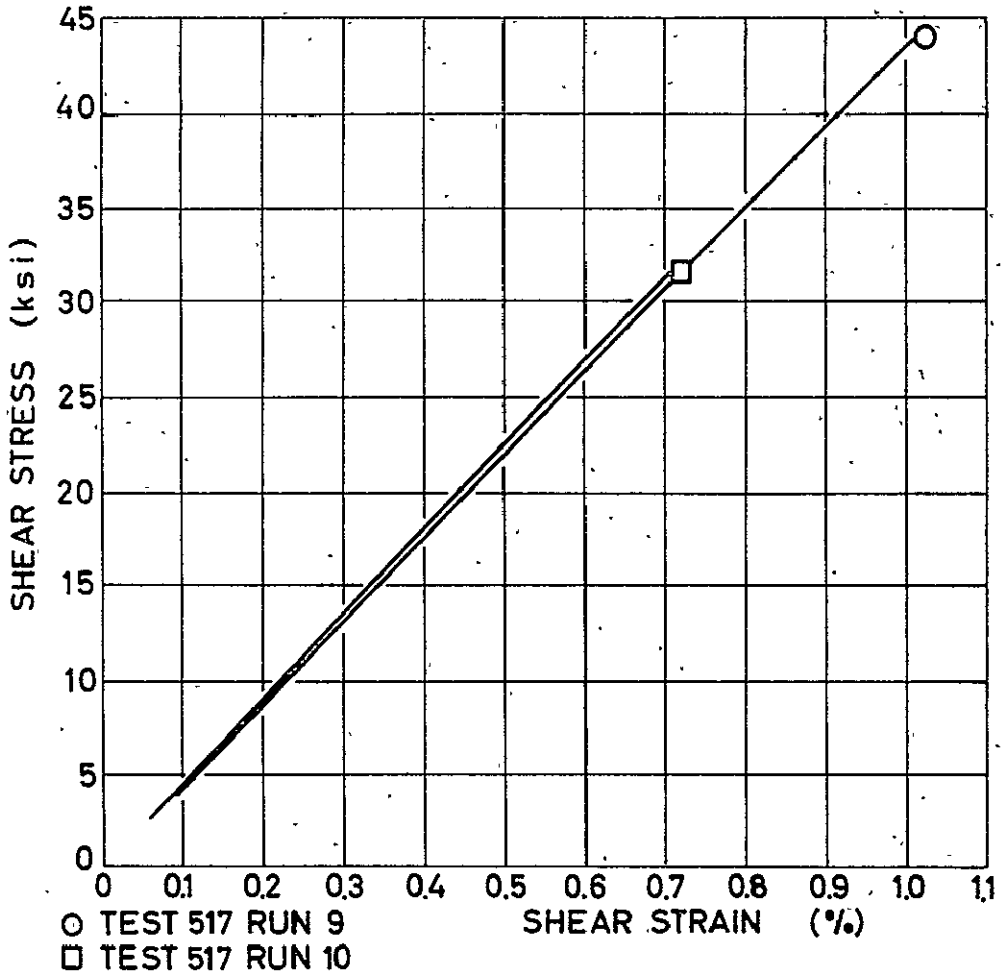


FIG. 10C SHEAR RESPONSE OF ±30° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES

K3



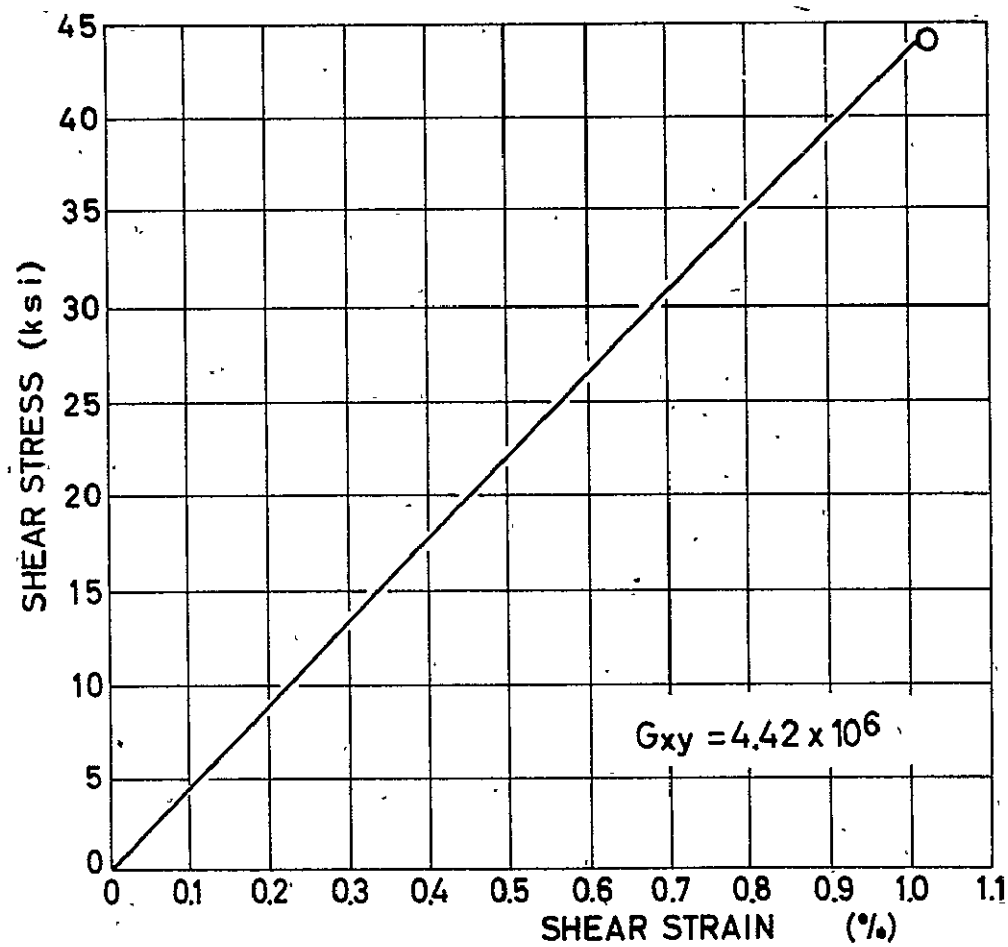
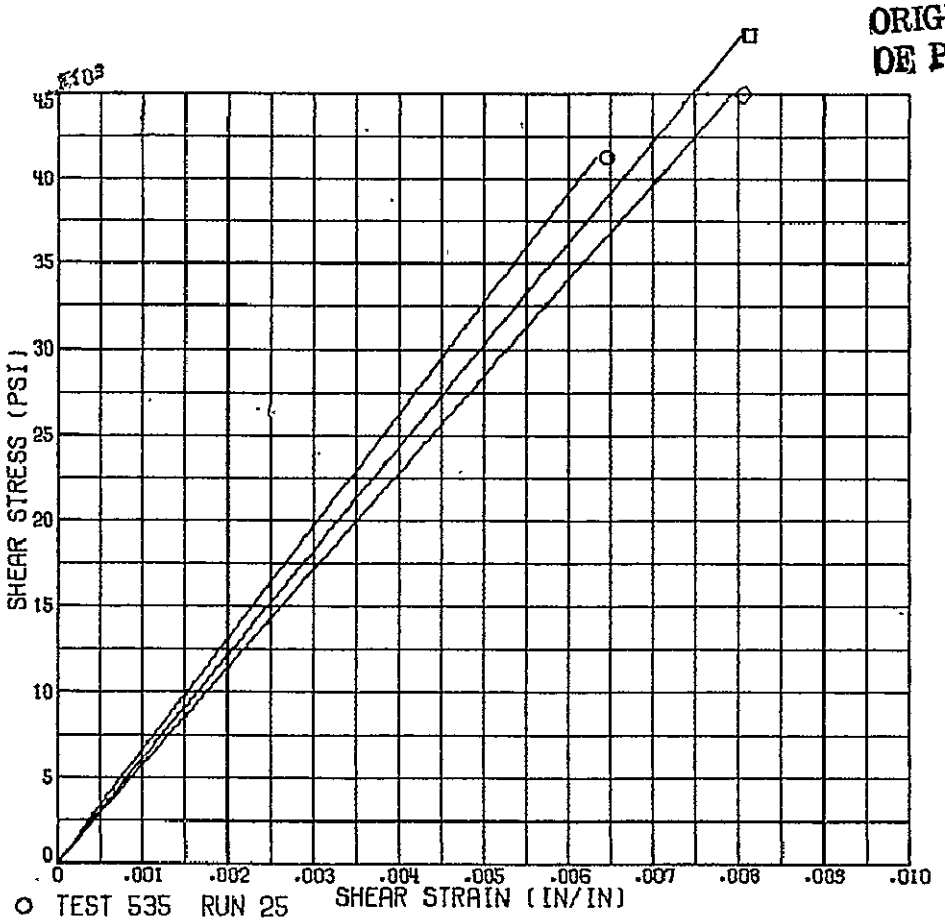


FIG. 11A SHEAR RESPONSE OF PLANAR SPECIMENS ±45° GR/EP

ORIGINAL PAGE IS
OF POOR QUALITY



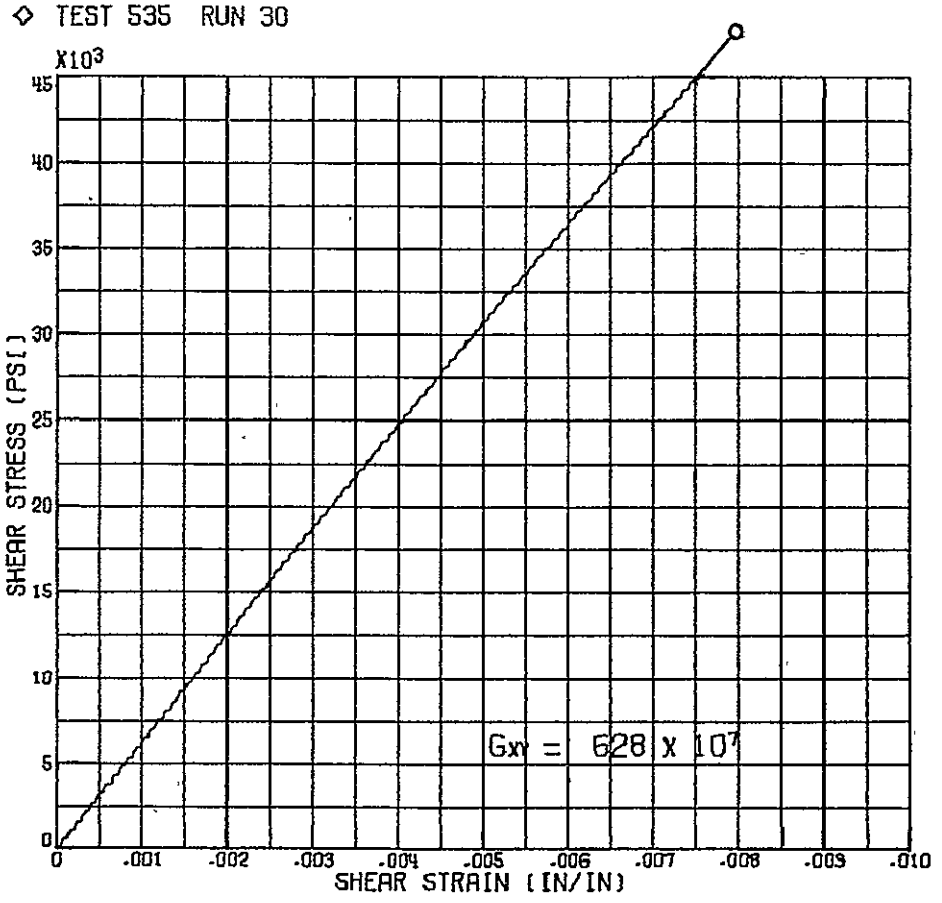


FIGURE 11B :-SHEAR RESPONSE OF TUBULAR SPECIMENS-[±45]ₛ GR/EP

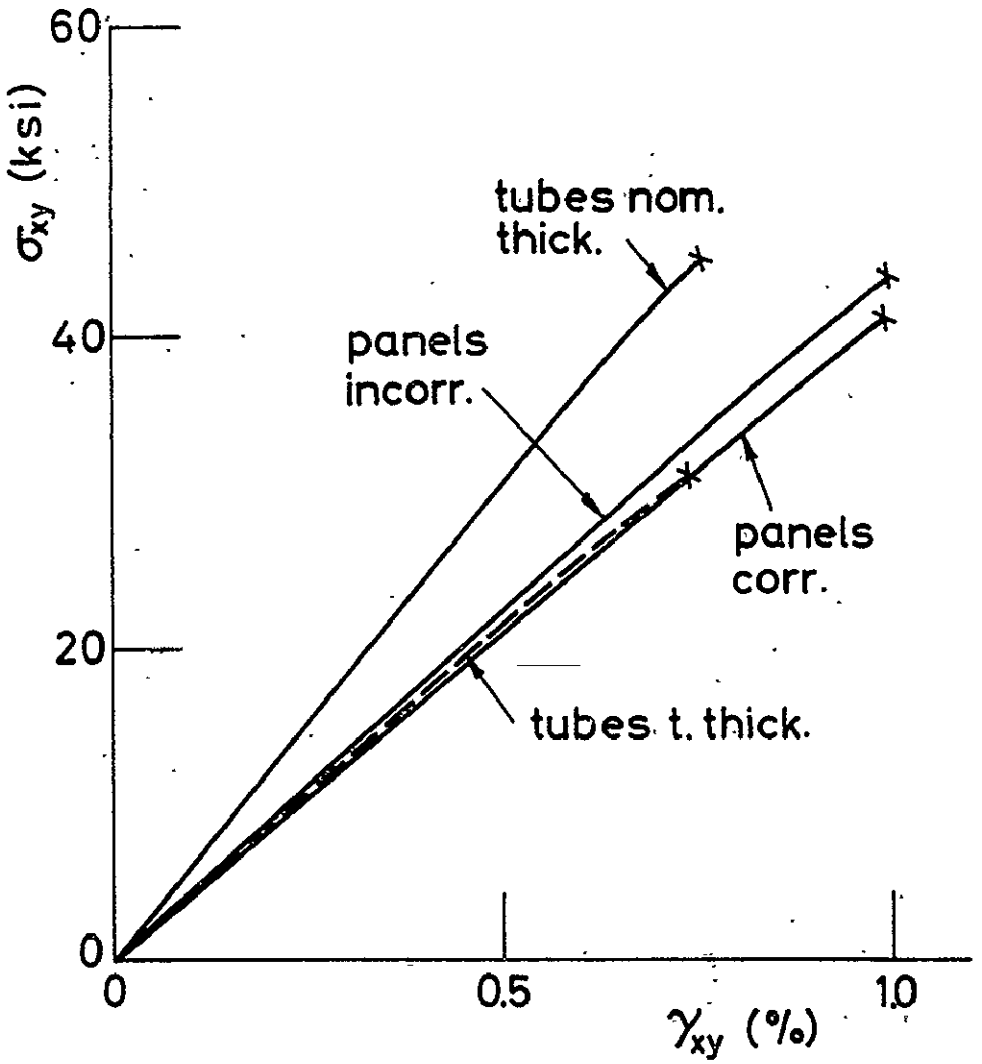
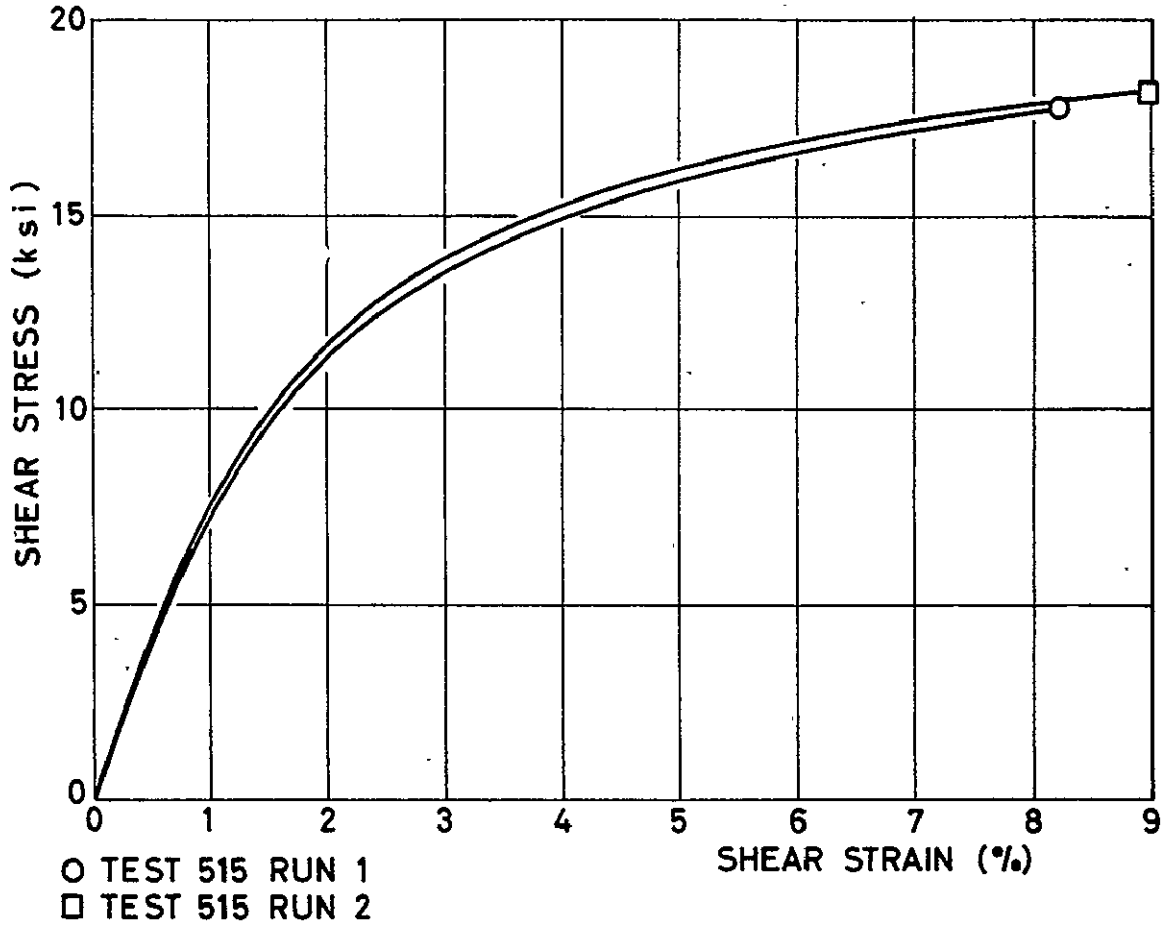


FIG. 11C SHEAR RESPONSE OF ±45° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES



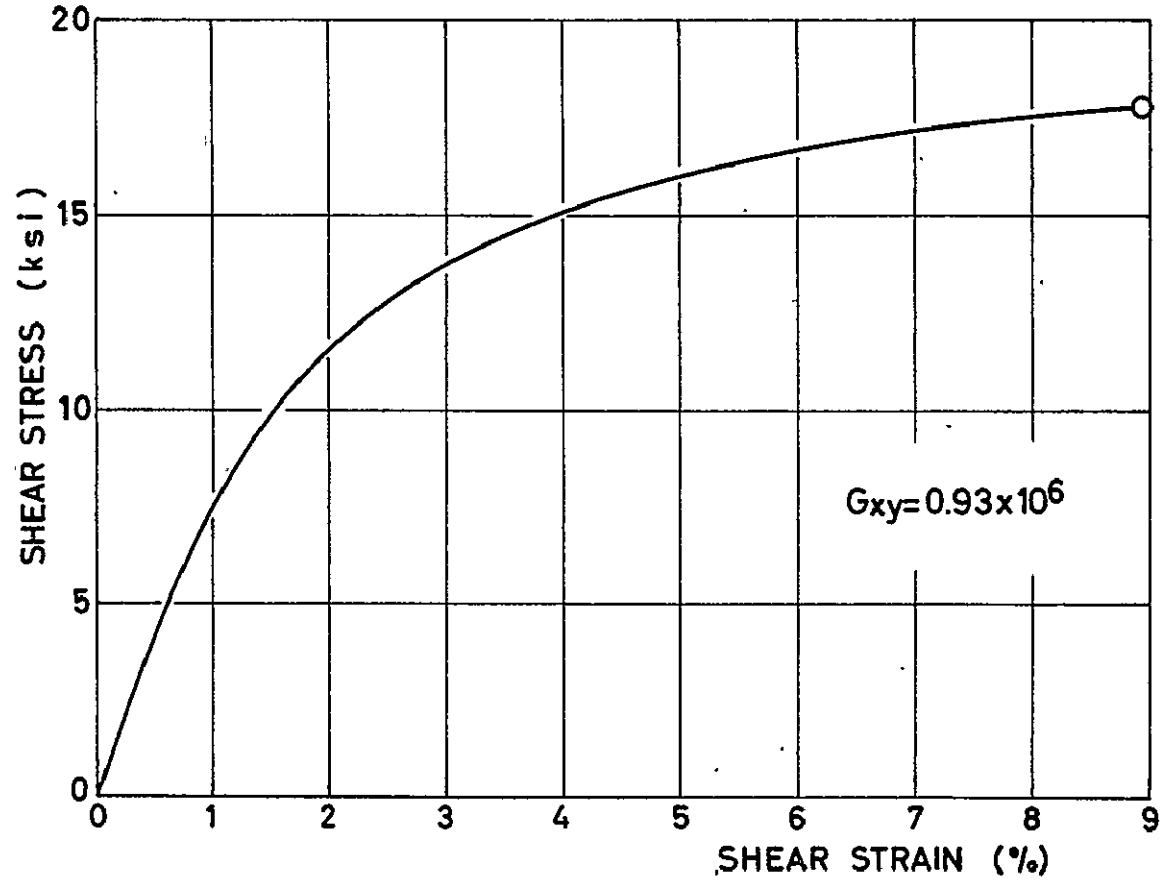
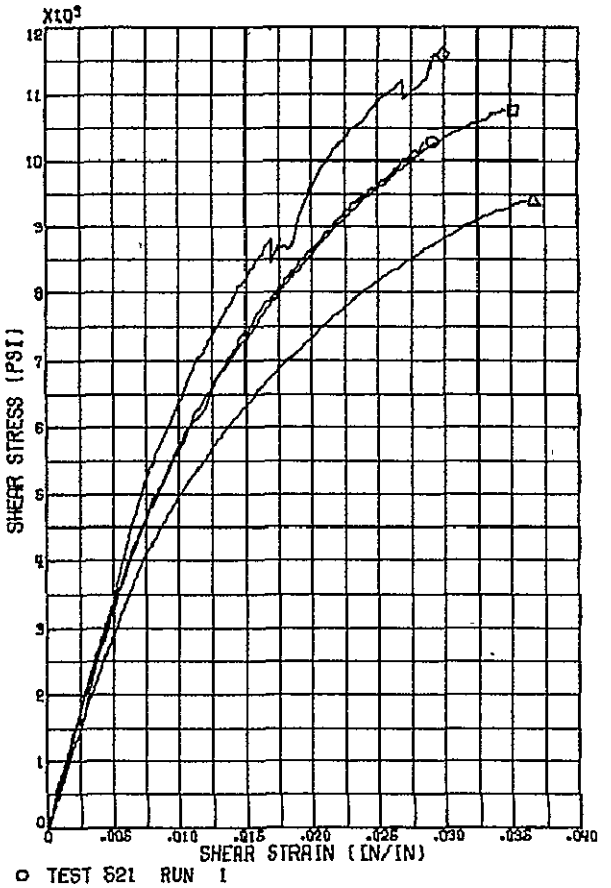


FIG. 12A SHEAR RESPONSE OF PLANAR SPECIMENS 0/90° GR/EP



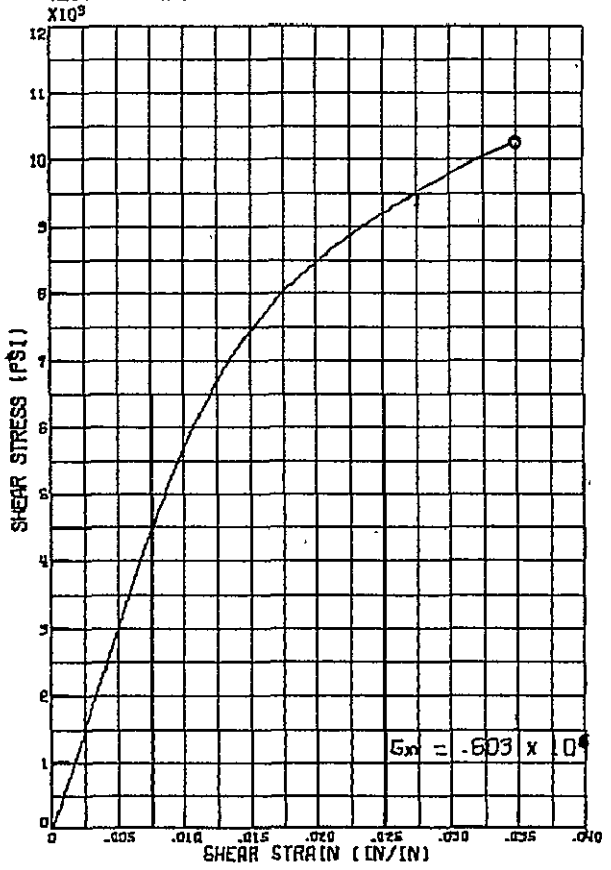


FIGURE 12B:-SHEAR RESPONSE OF TUBULAR SPECIMENS-[0/90]$_s$ GR/EP

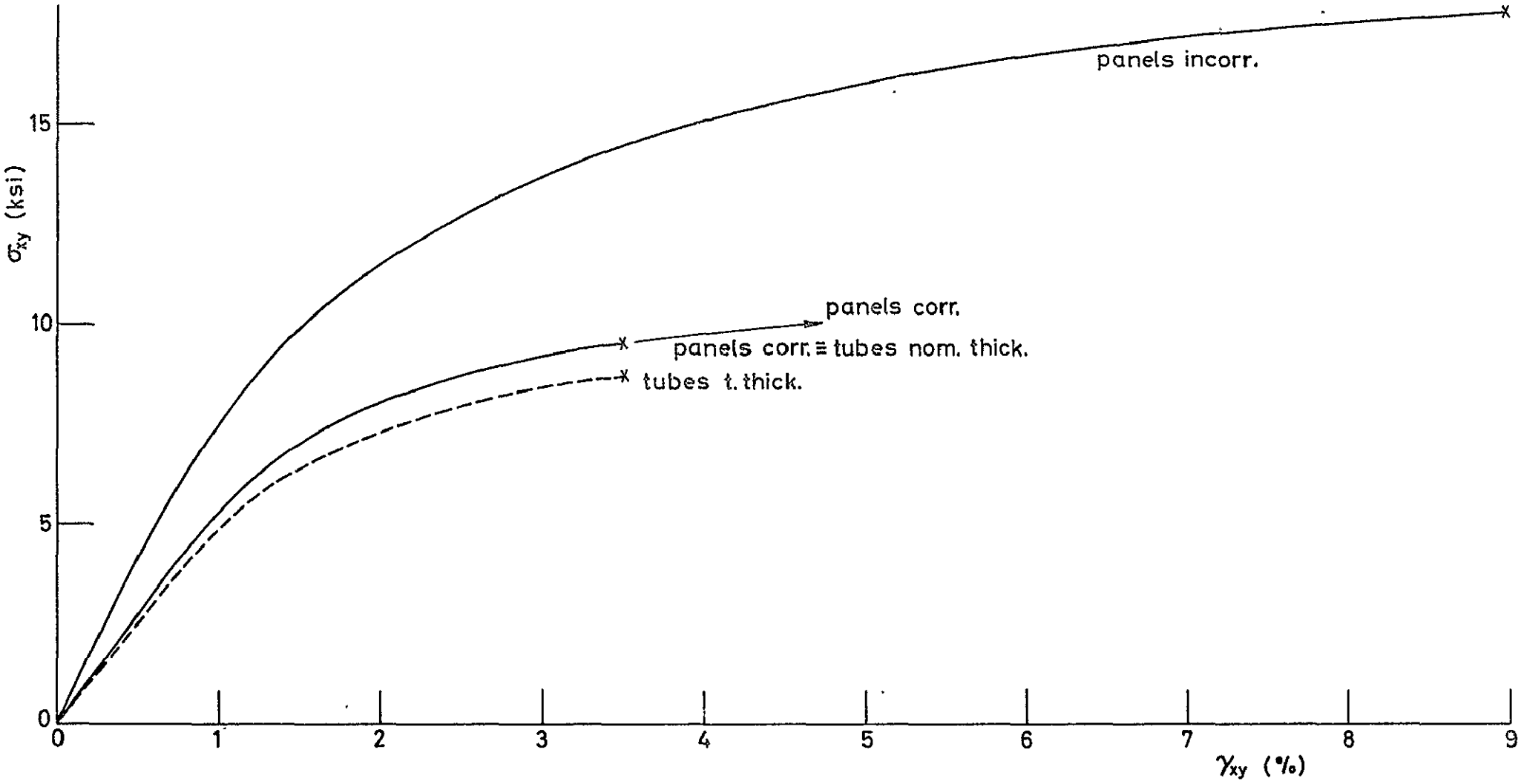
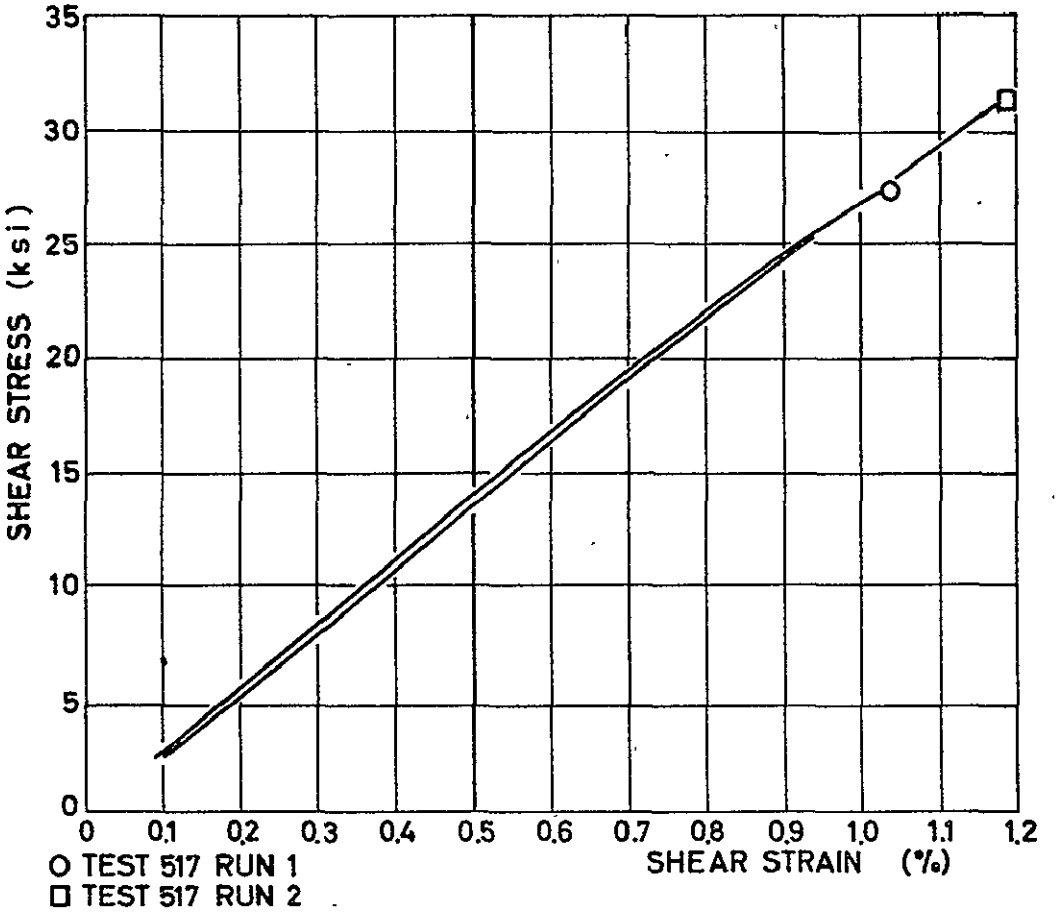


FIG. 12C SHEAR RESPONSE OF 0/90° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES



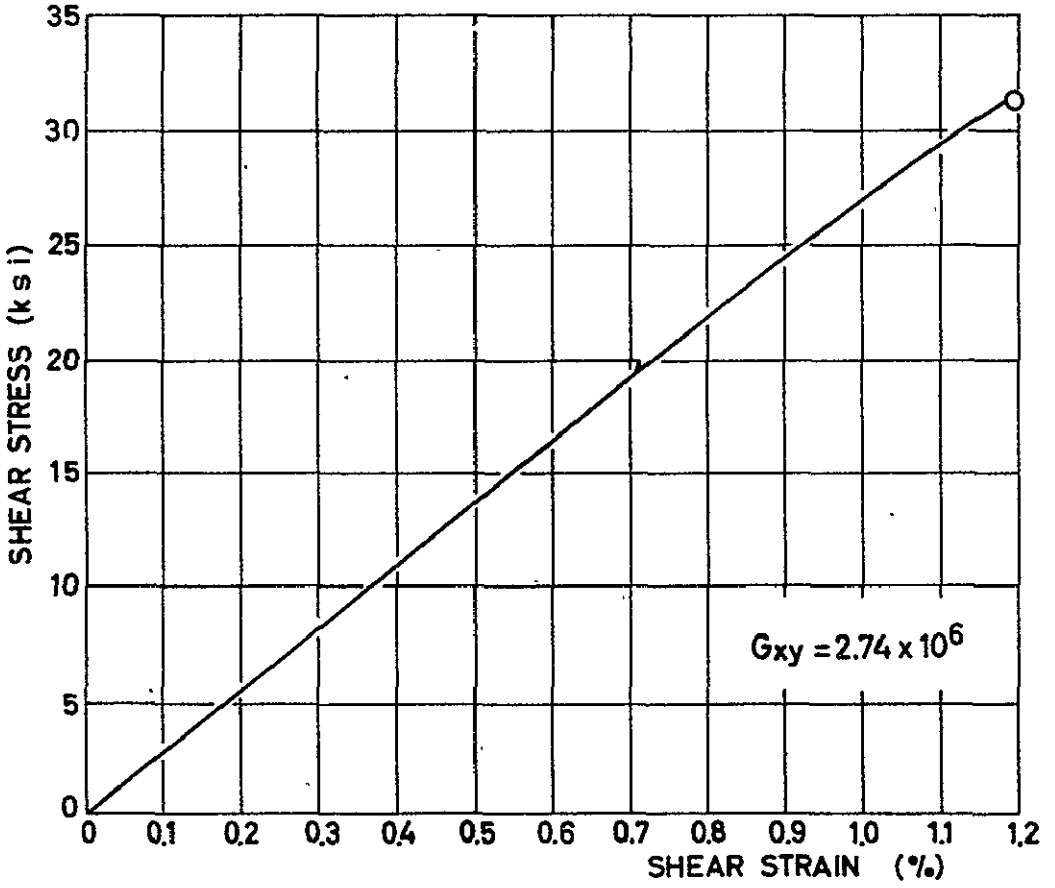


FIG. 13A SHEAR RESPONSE OF PLANAR SPECIMENS 0/±45/90° GR/EP

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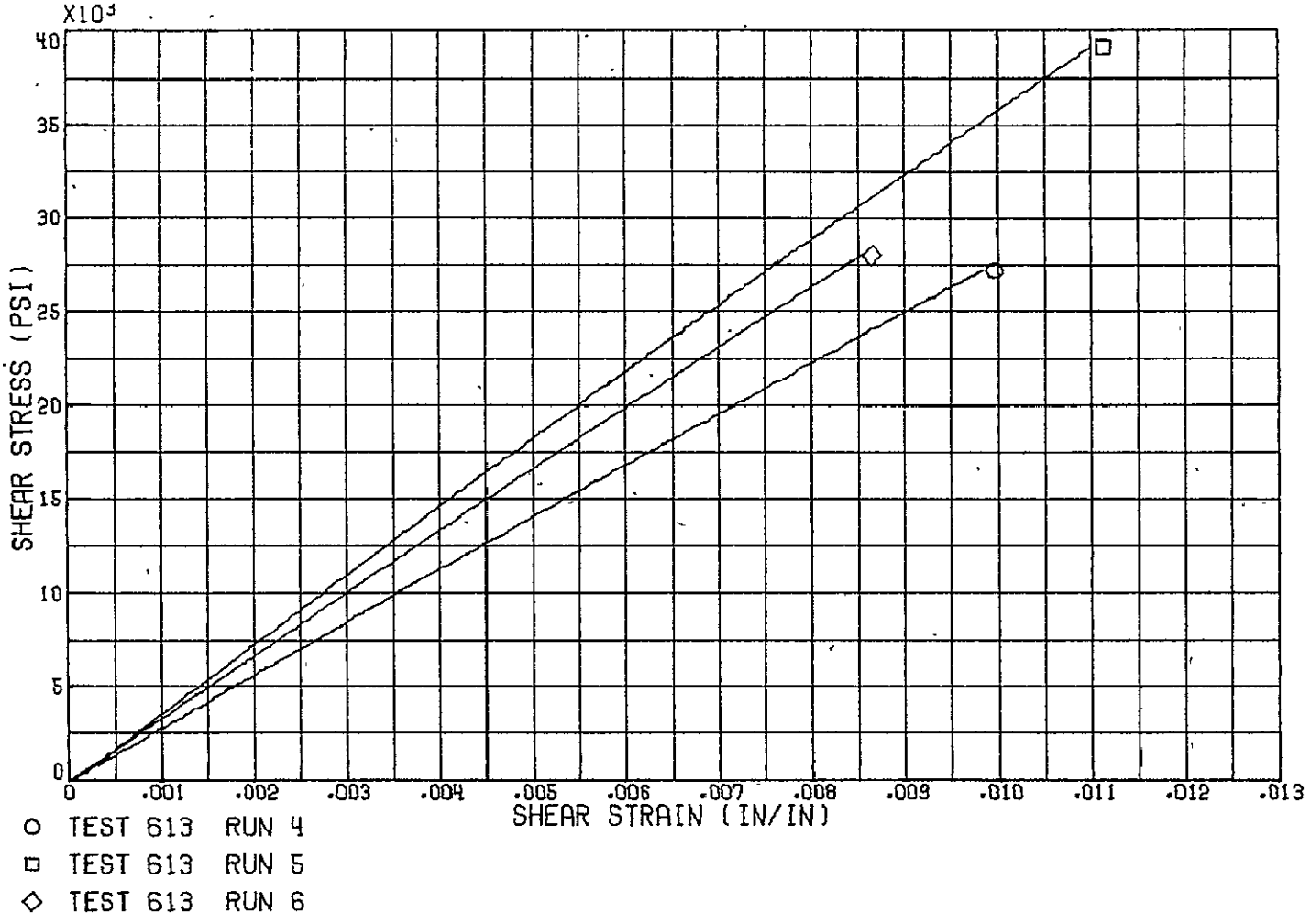


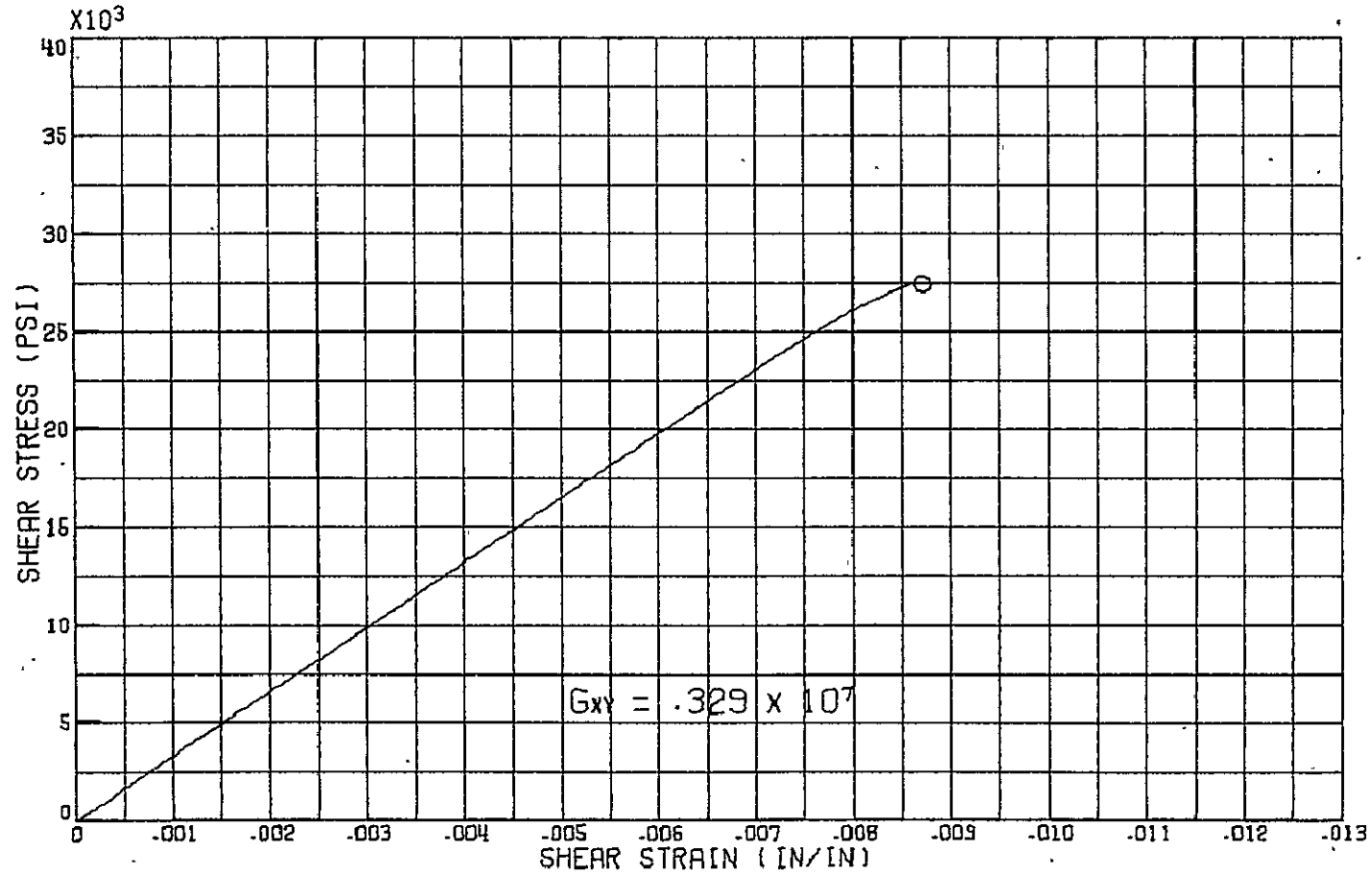


FIGURE 13B ;-SHEAR RESPONSE OF TUBULAR SPECIMENS-[0/±45/90]$_S$ GR/EP

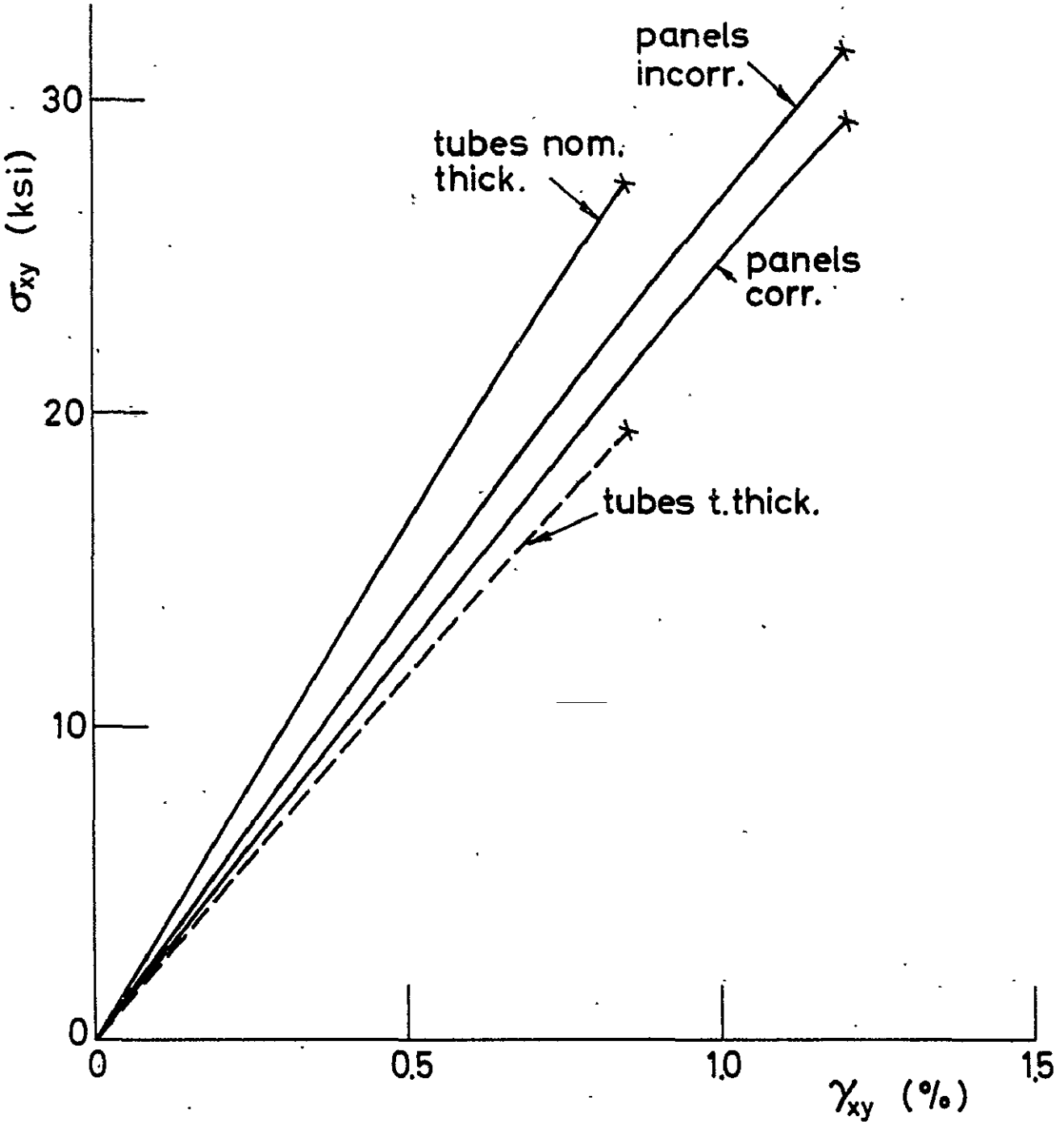
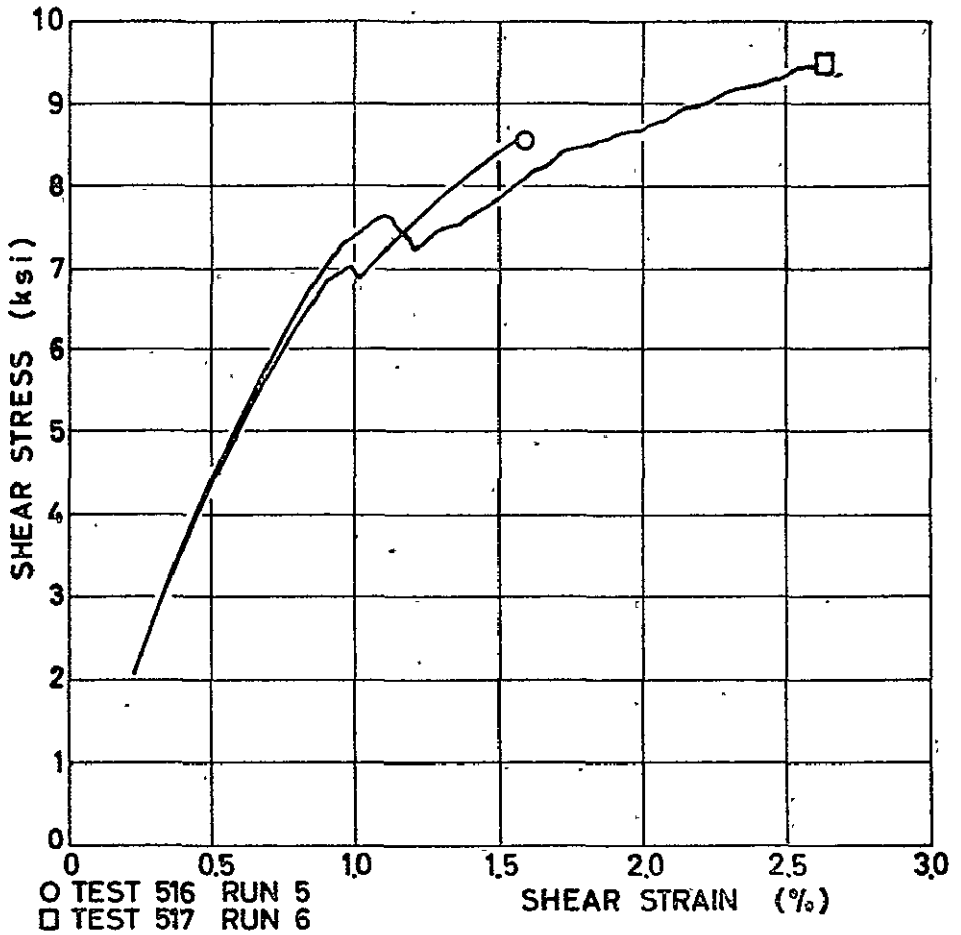


FIG. 13C SHEAR RESPONSE OF 0/±45/90° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES



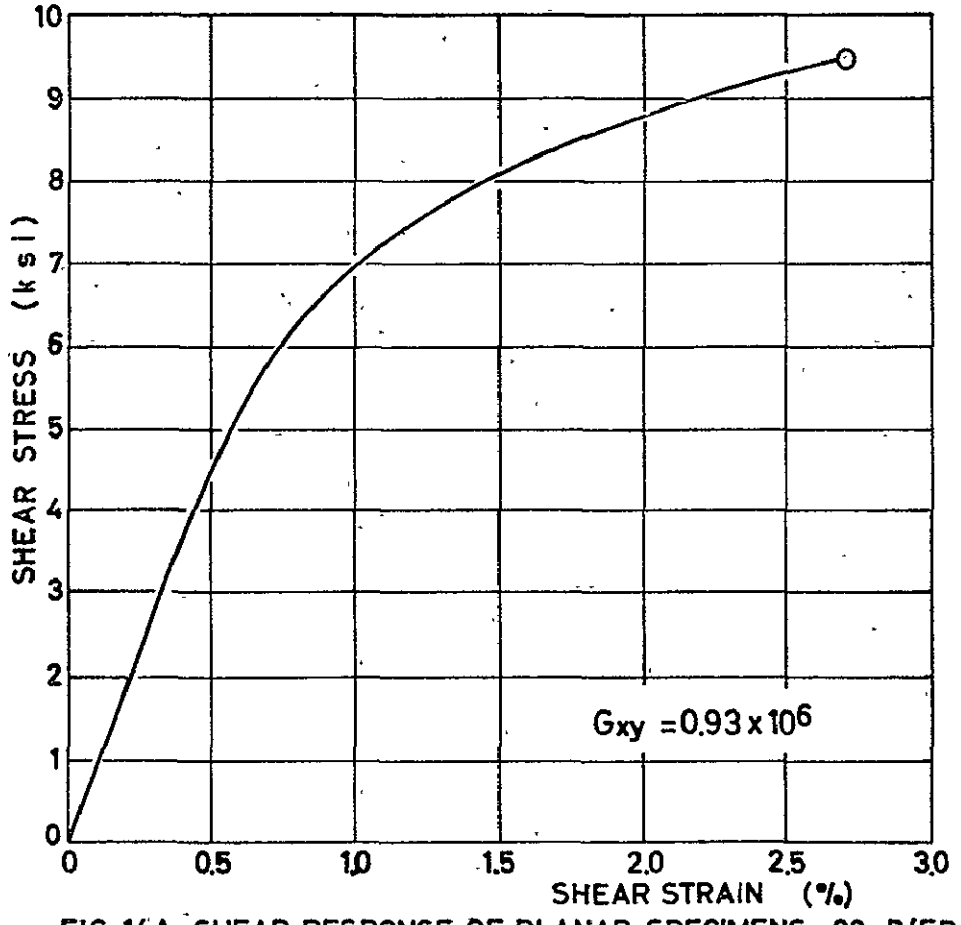
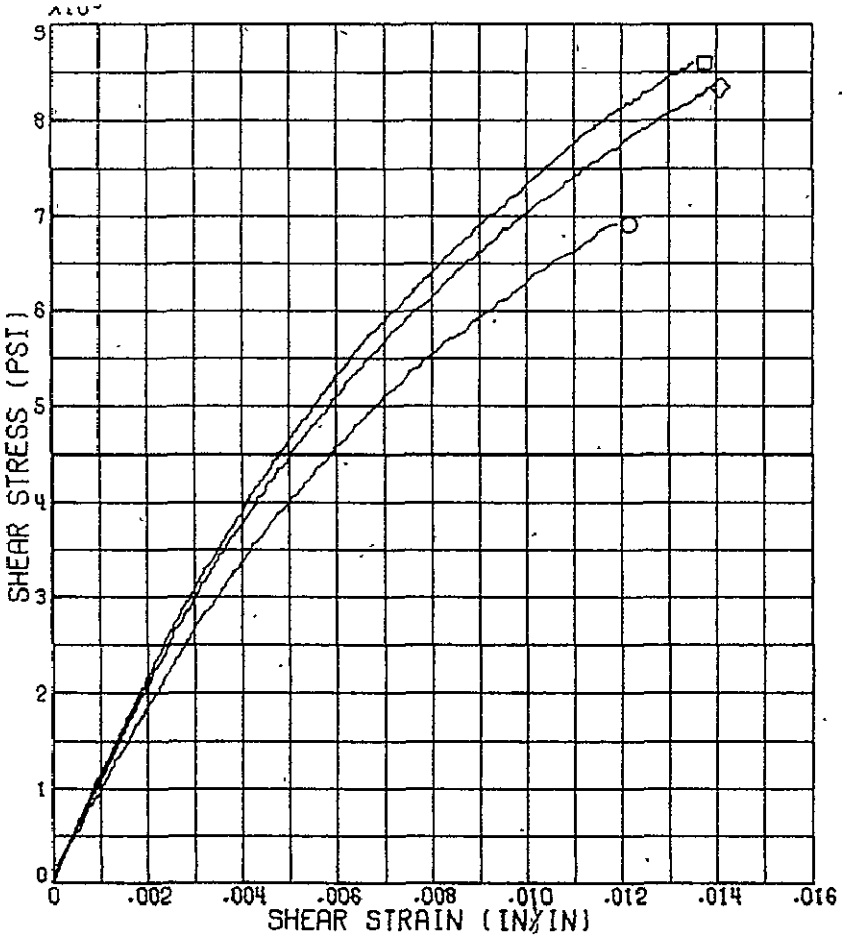


FIG. 14A SHEAR RESPONSE OF PLANAR SPECIMENS 0° B/EP



○ TEST 535 RUN 14
□ TEST 535 RUN 15
◇ TEST 535 RUN 16

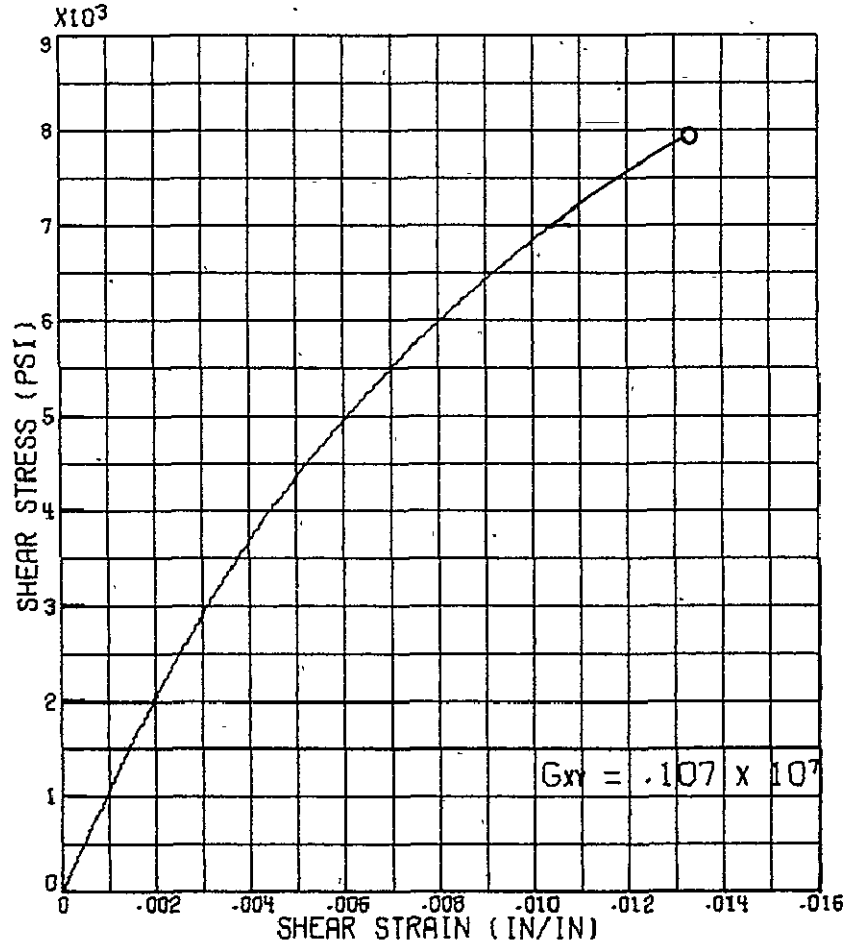


FIGURE 14B:-SHEAR RESPONSE OF TUBULAR SPECIMENS-C90° B/EP

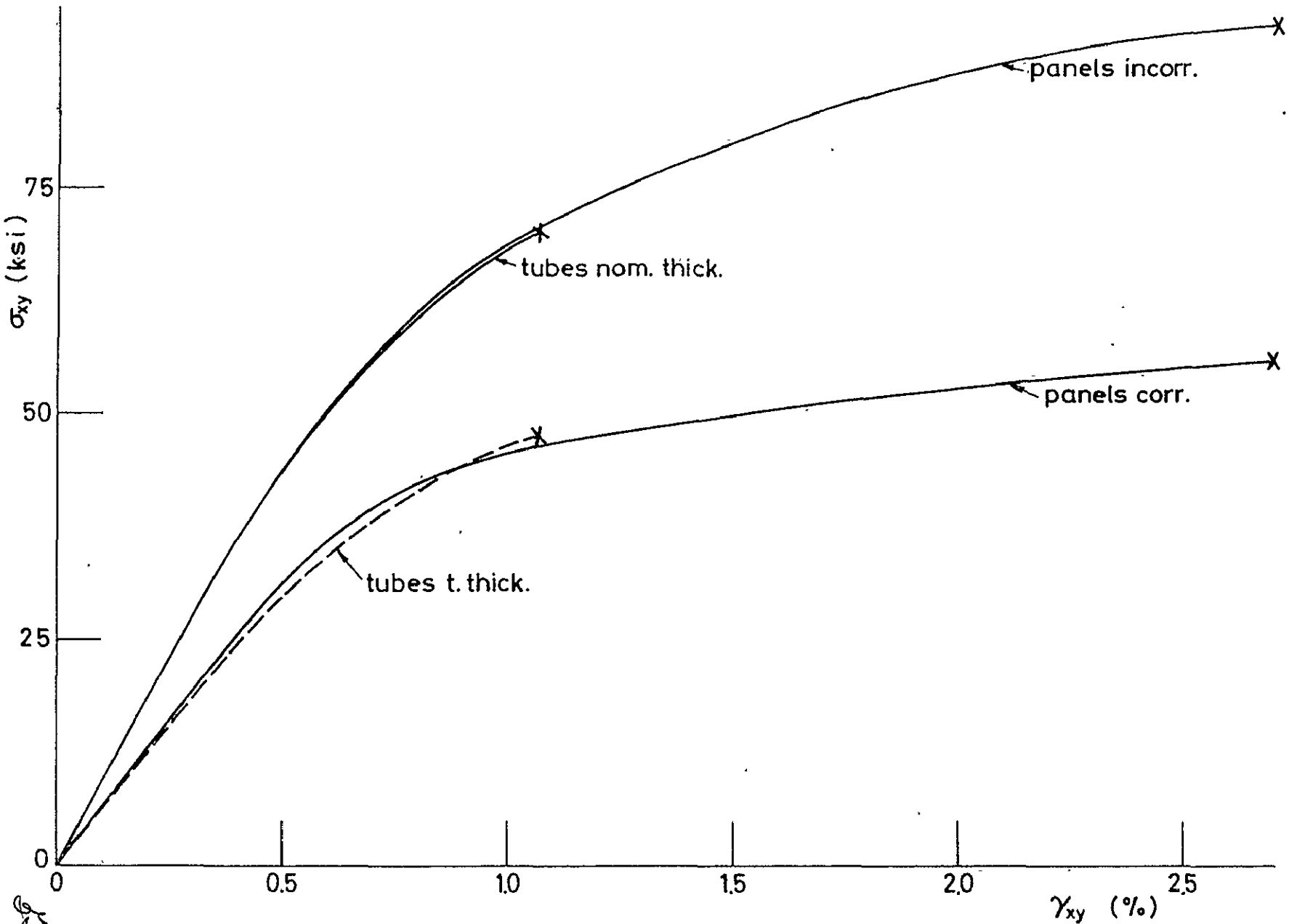
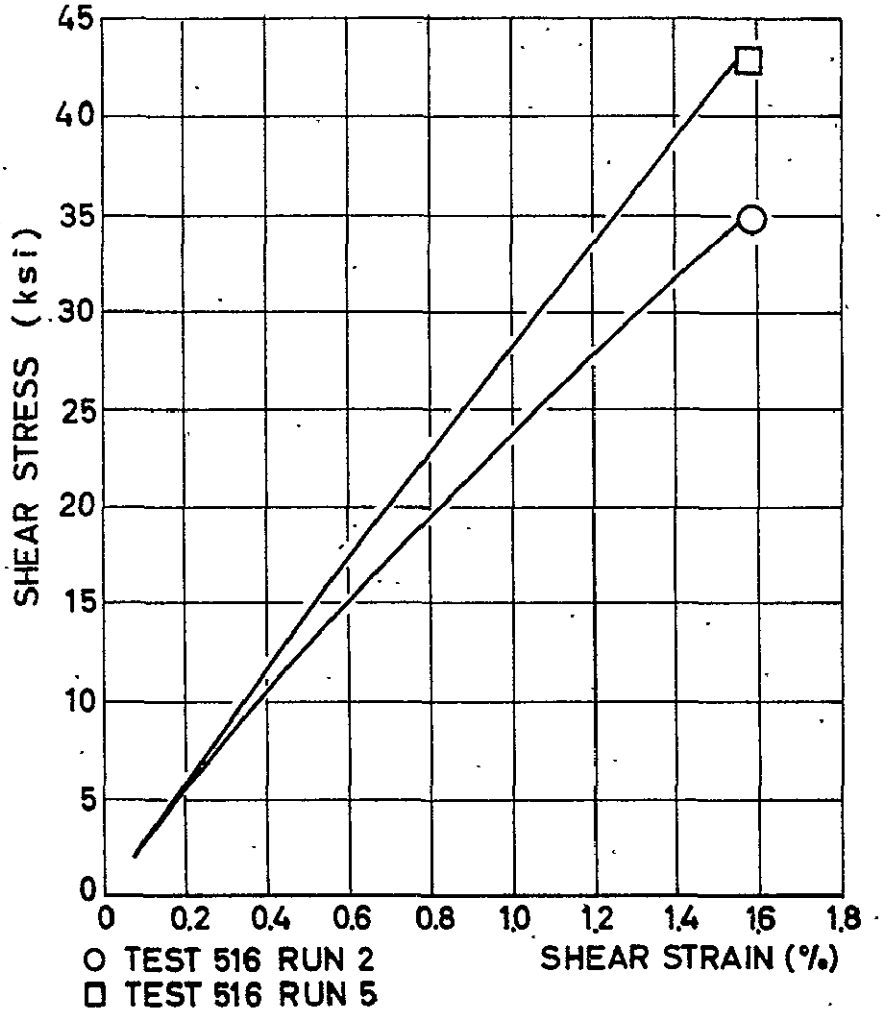


FIG. 14C SHEAR RESPONSE OF 0° AVCO 5505/5.6 MIL BORON-EPOXY LAMINATES



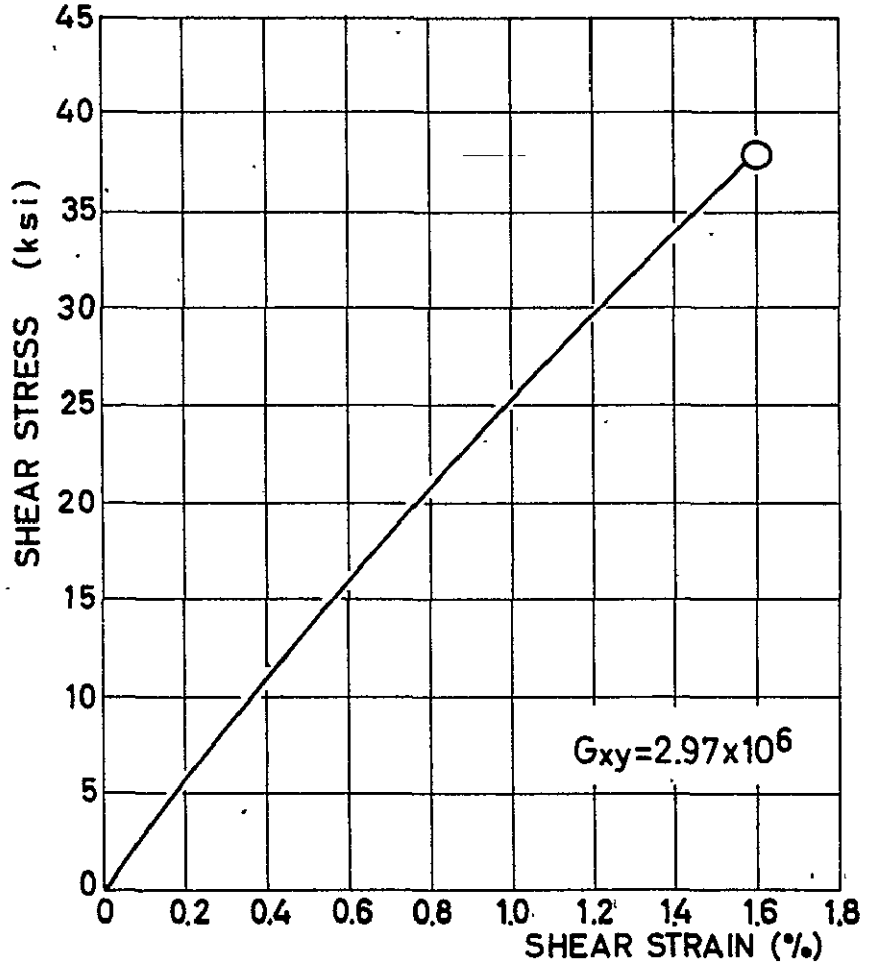


FIG. 15 A SHEAR RESPONSE OF PLANAR SPECIMENS ±15° B/EP

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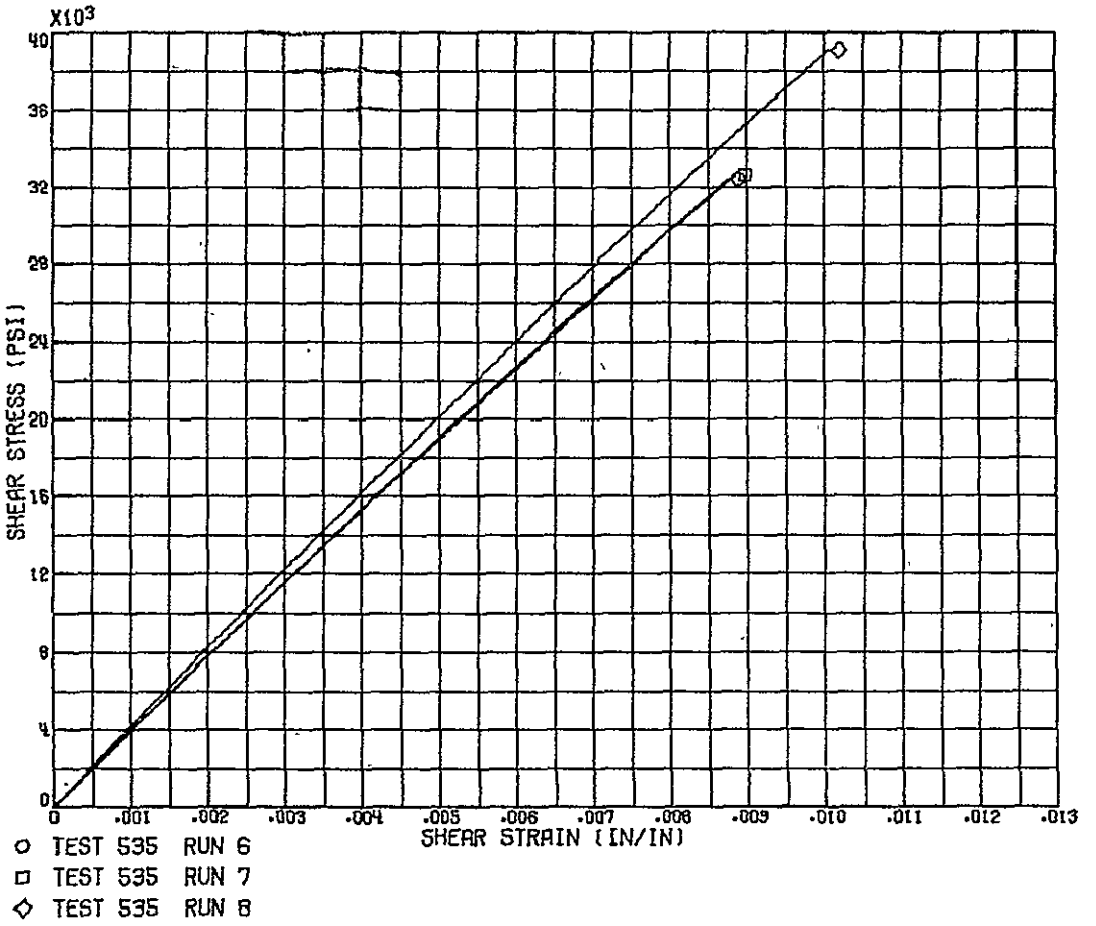


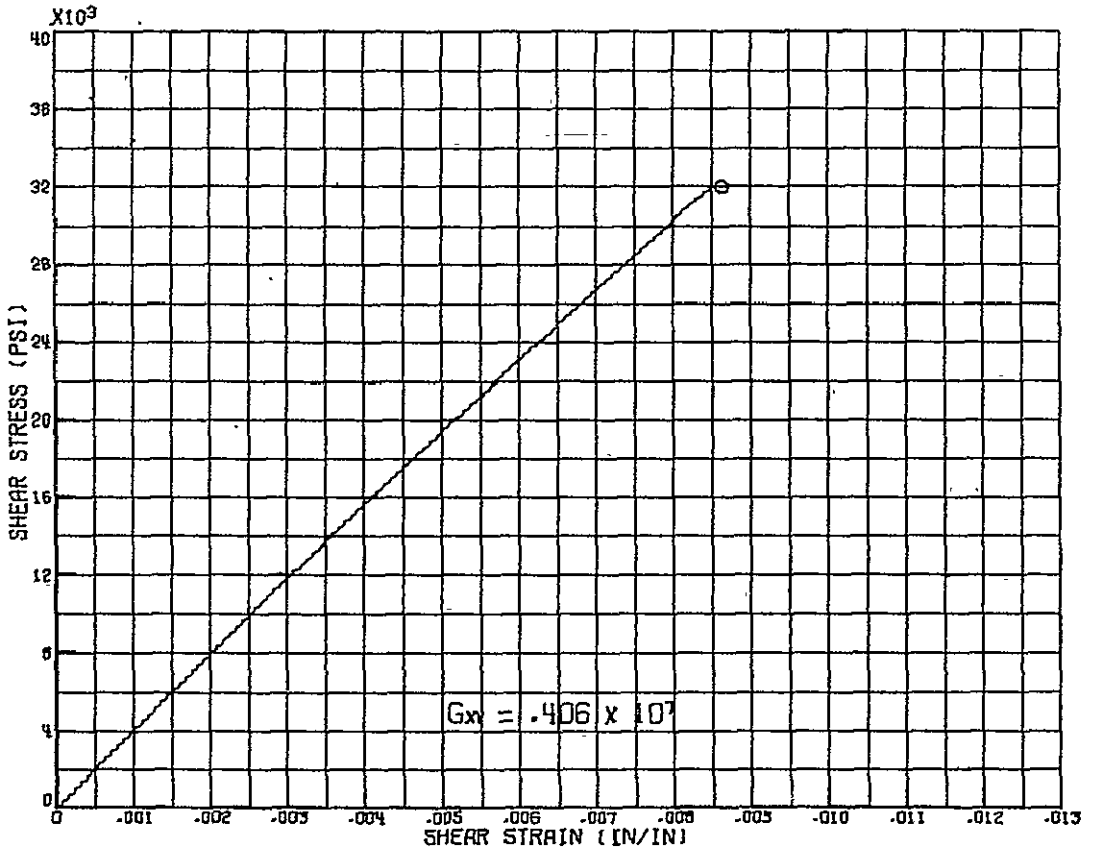


FIGURE 15B:-SHEAR RESPONSE OF TUBULAR SPECIMENS-C±15° B/EP

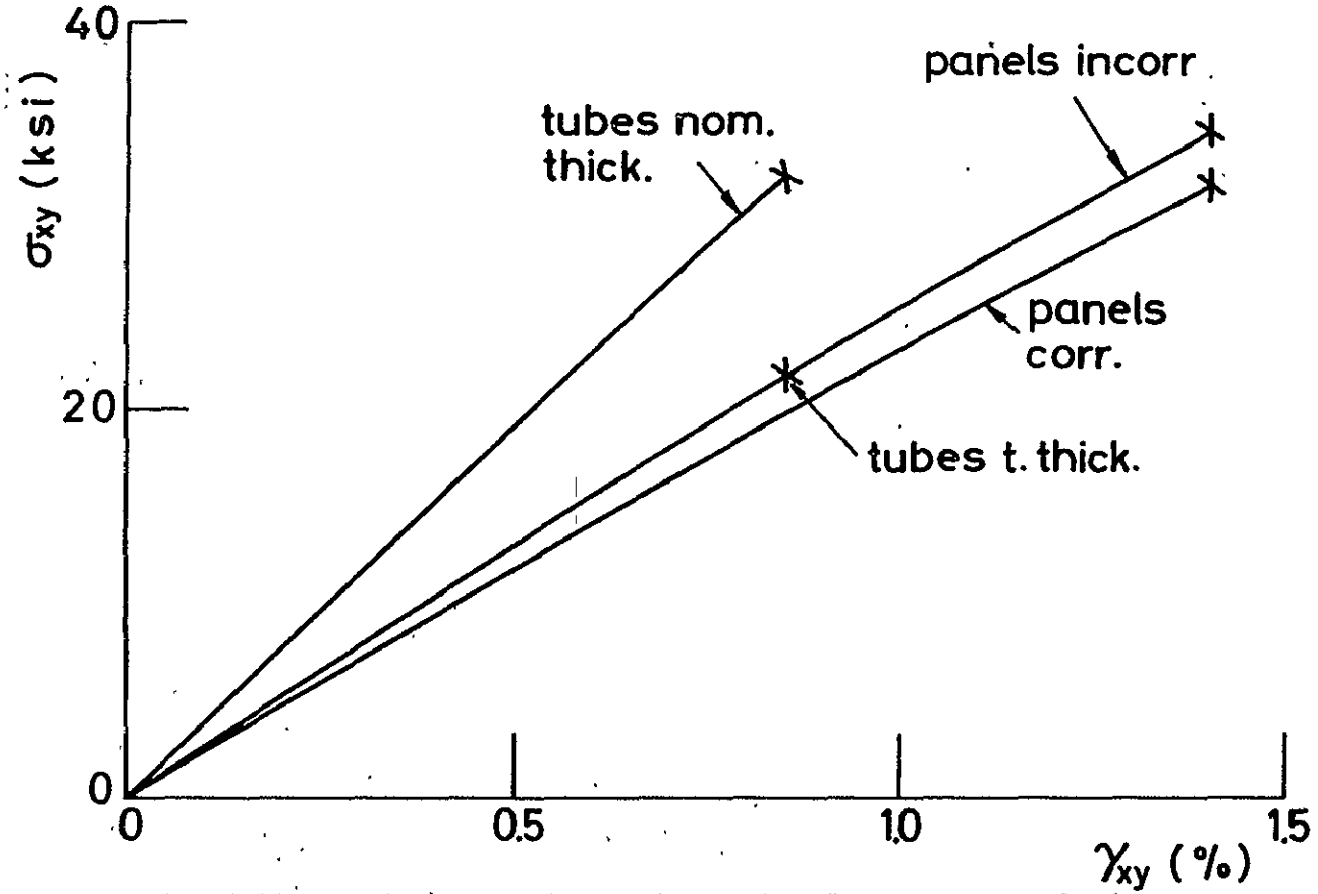
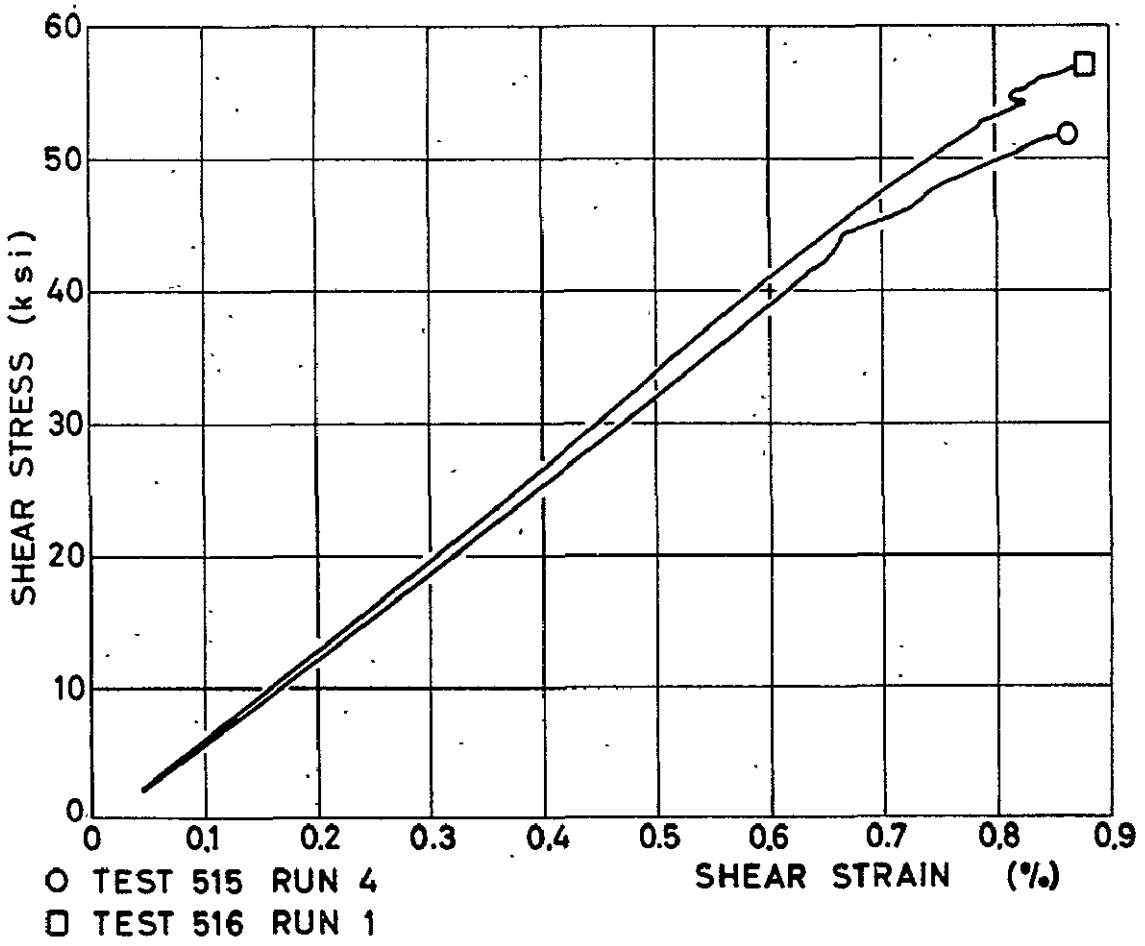


FIG. 15C SHEAR RESPONSE OF ±15° AVCO 5505/5.6 MIL BORON-EPOXY LAMINATES



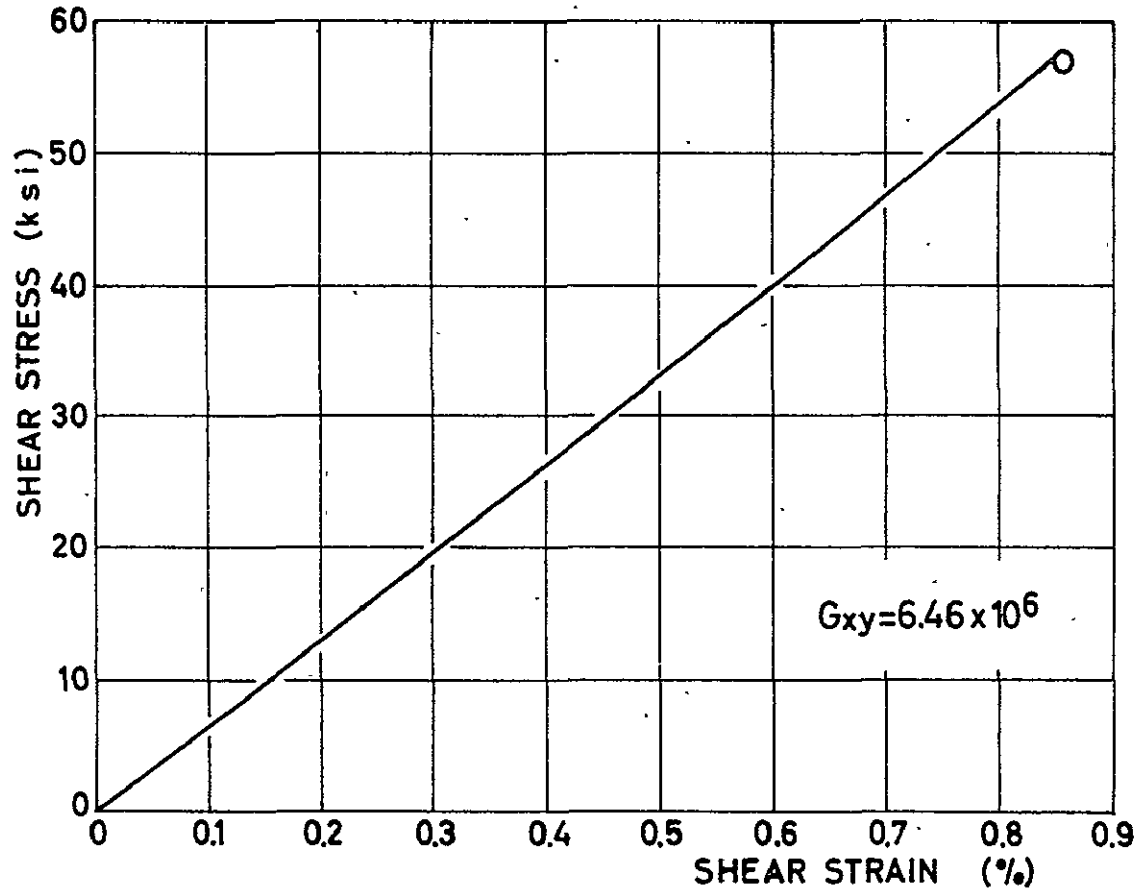
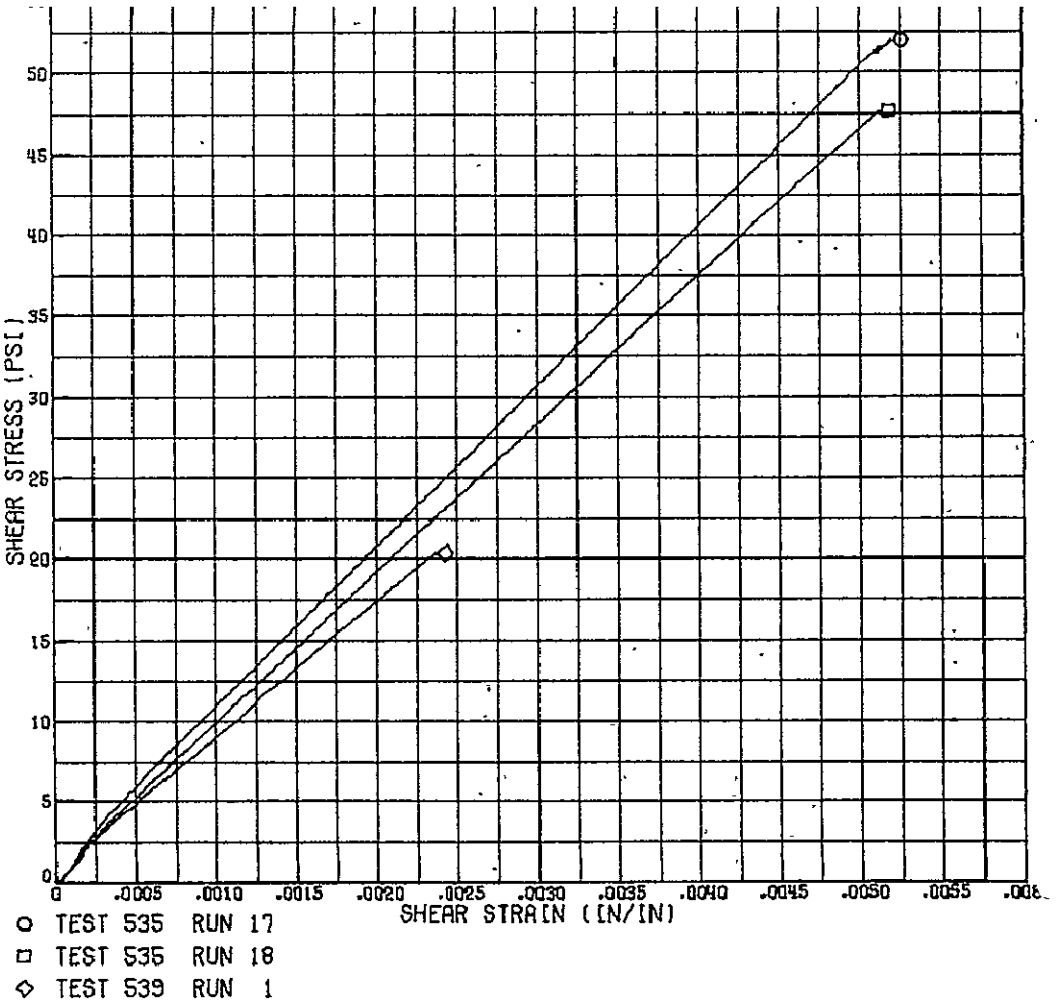


FIG. 16A SHEAR RESPONSE OF PLANAR SPECIMENS ±30° B/EP



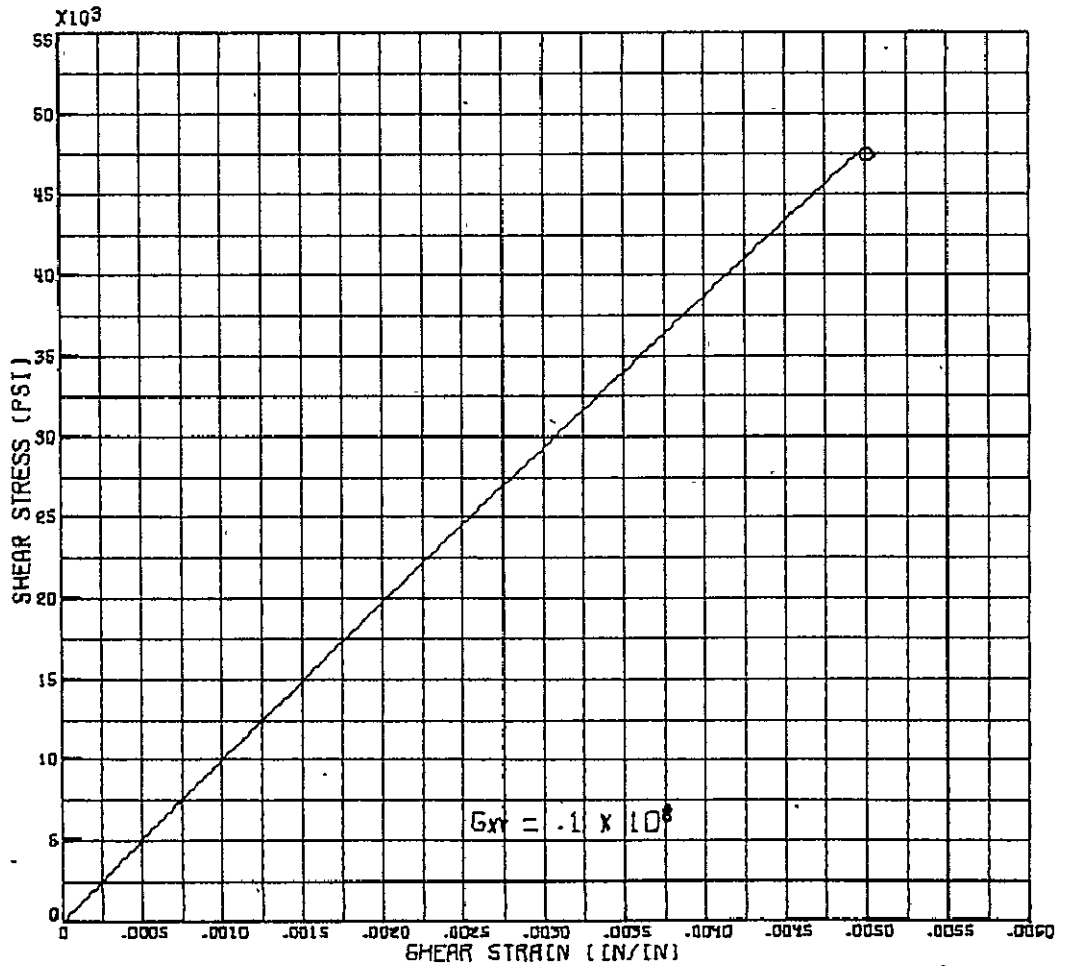


FIGURE 16B :- SHEAR RESPONSE OF TUBULAR SPECIMENS-C±30° B/EP

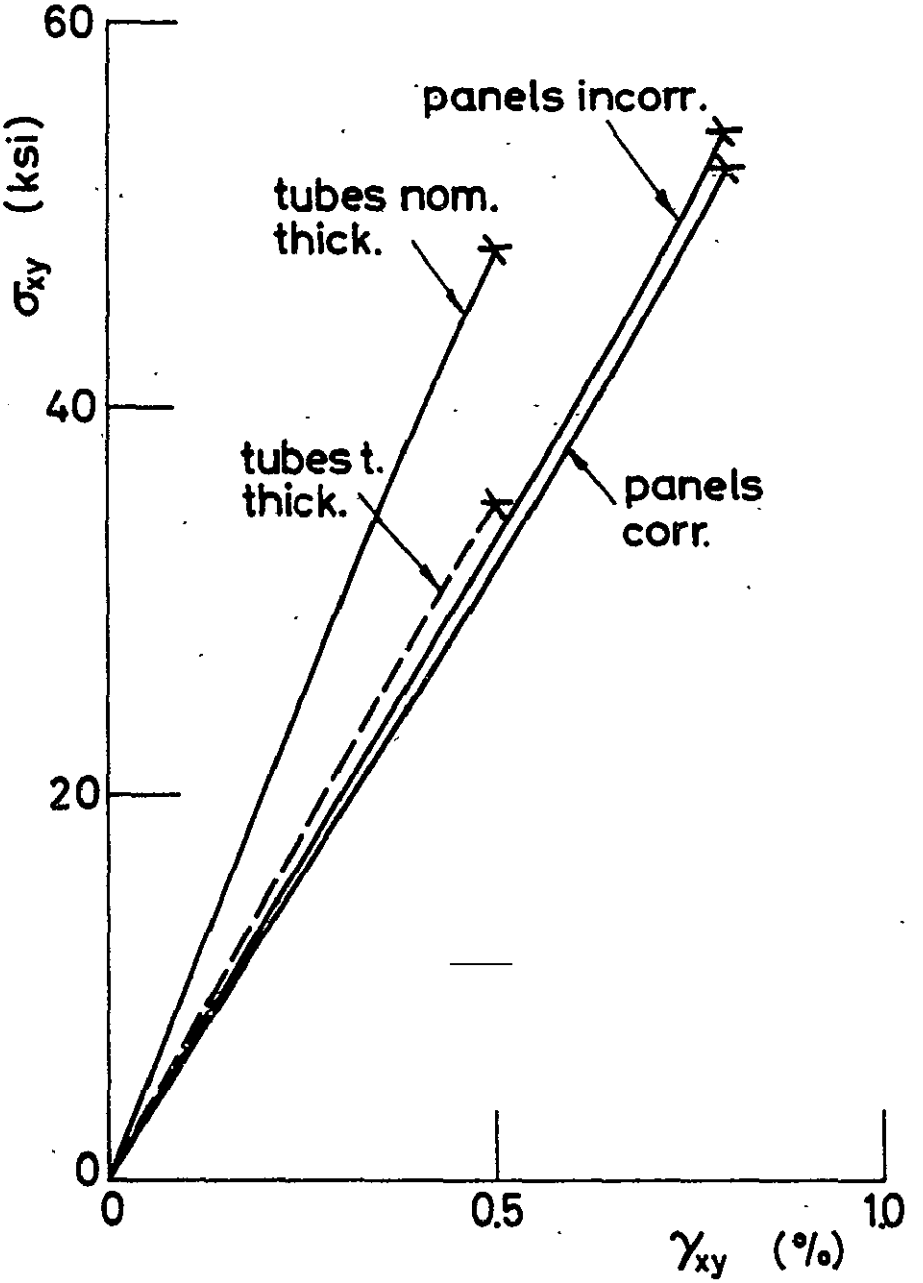
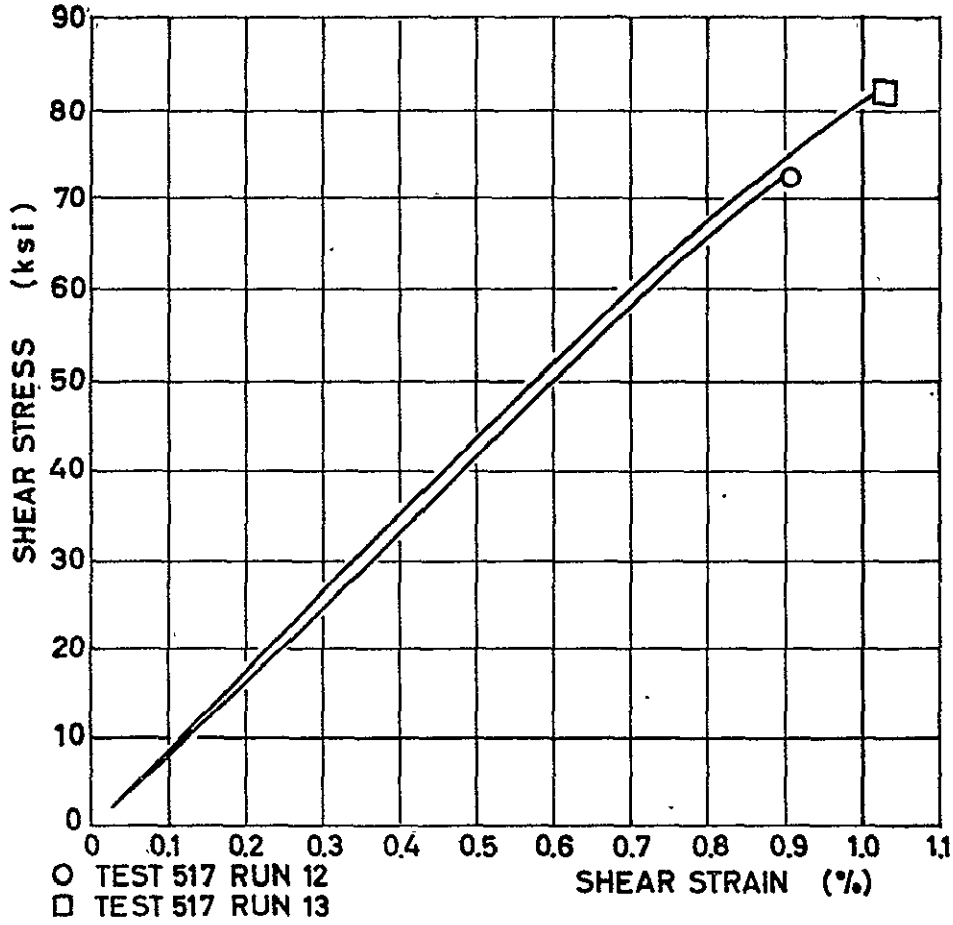


FIG. 16C SHEAR RESPONSE OF ±30° AVCO 5505/5.6 MIL. BORON-EPOXY LAMINATES



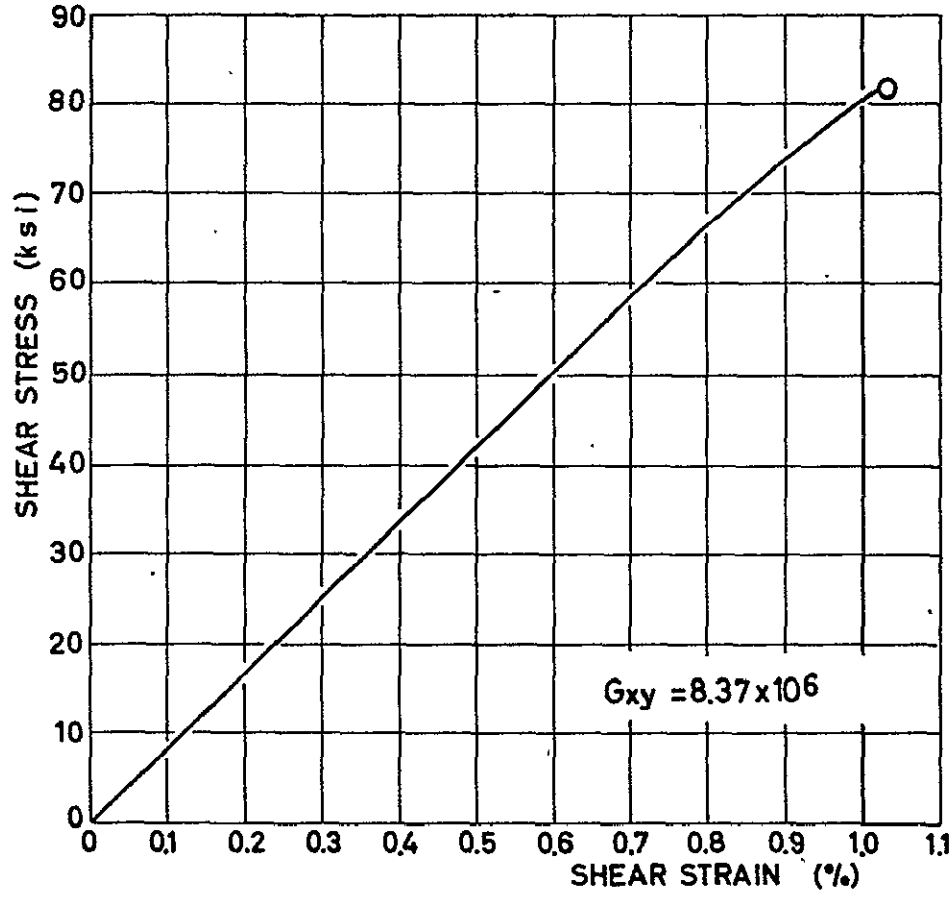
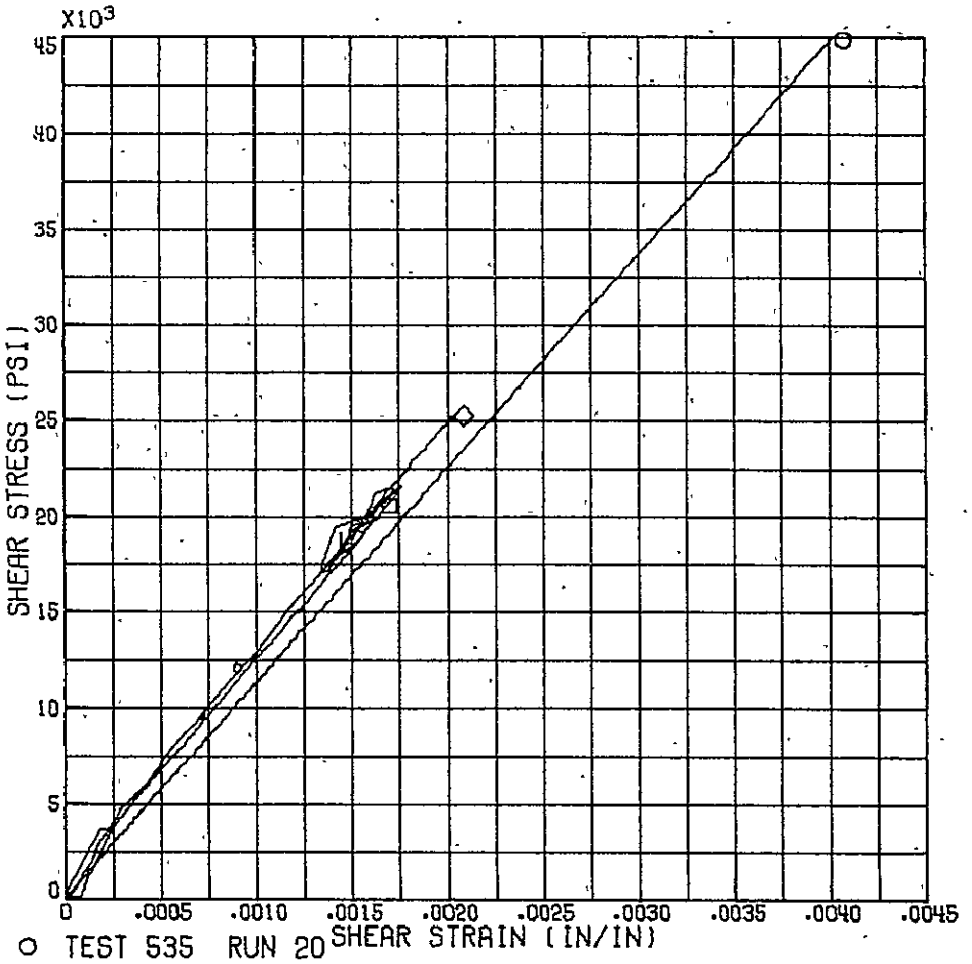


FIG. 17A SHEAR RESPONSE OF PLANAR SPECIMENS ±45° B/EP



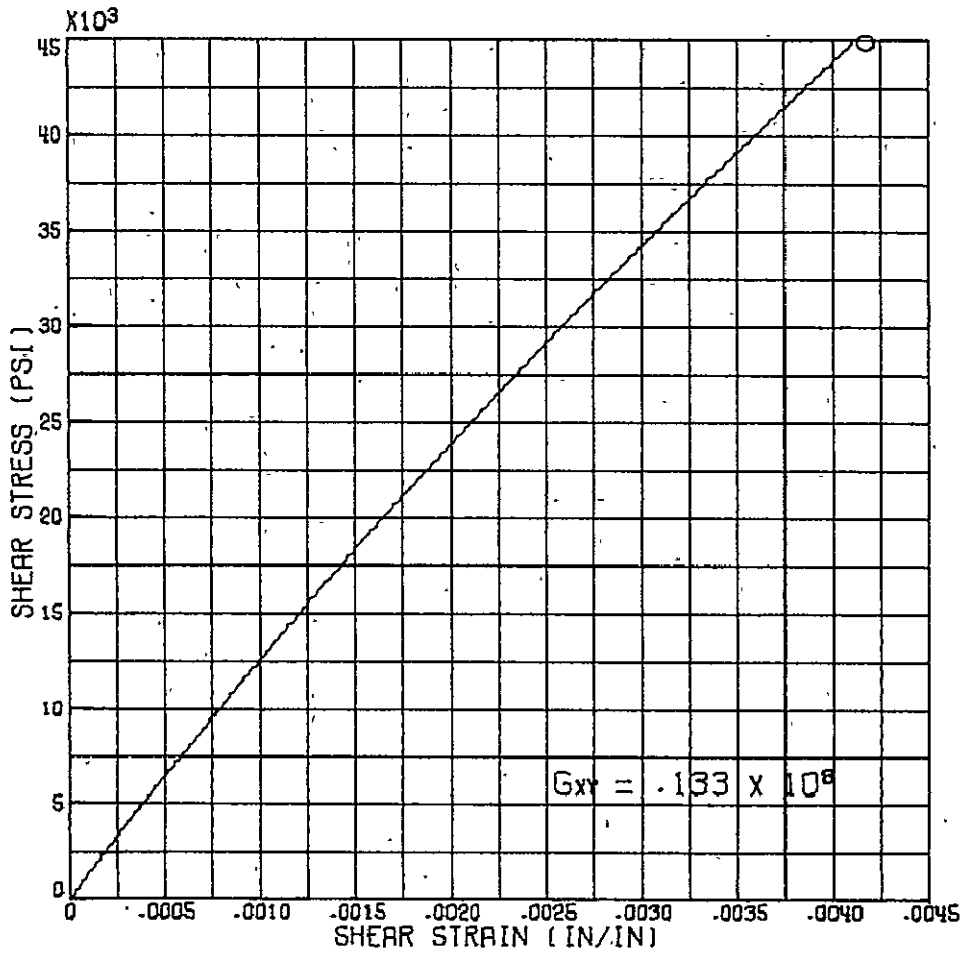


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FIGURE 17B ;-SHEAR RESPONSE OF TUBULAR SPECIMENS-[±45°] B/EP

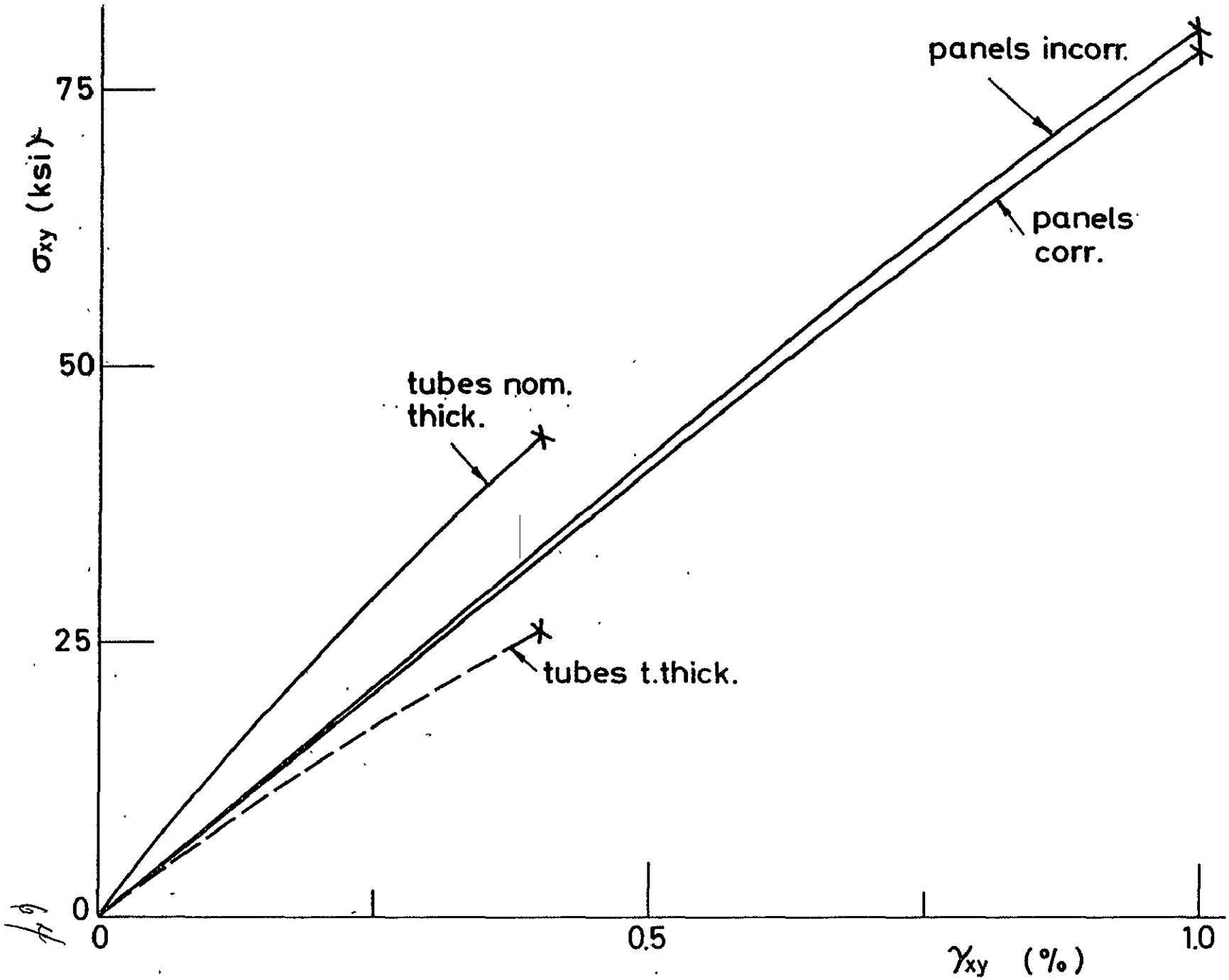
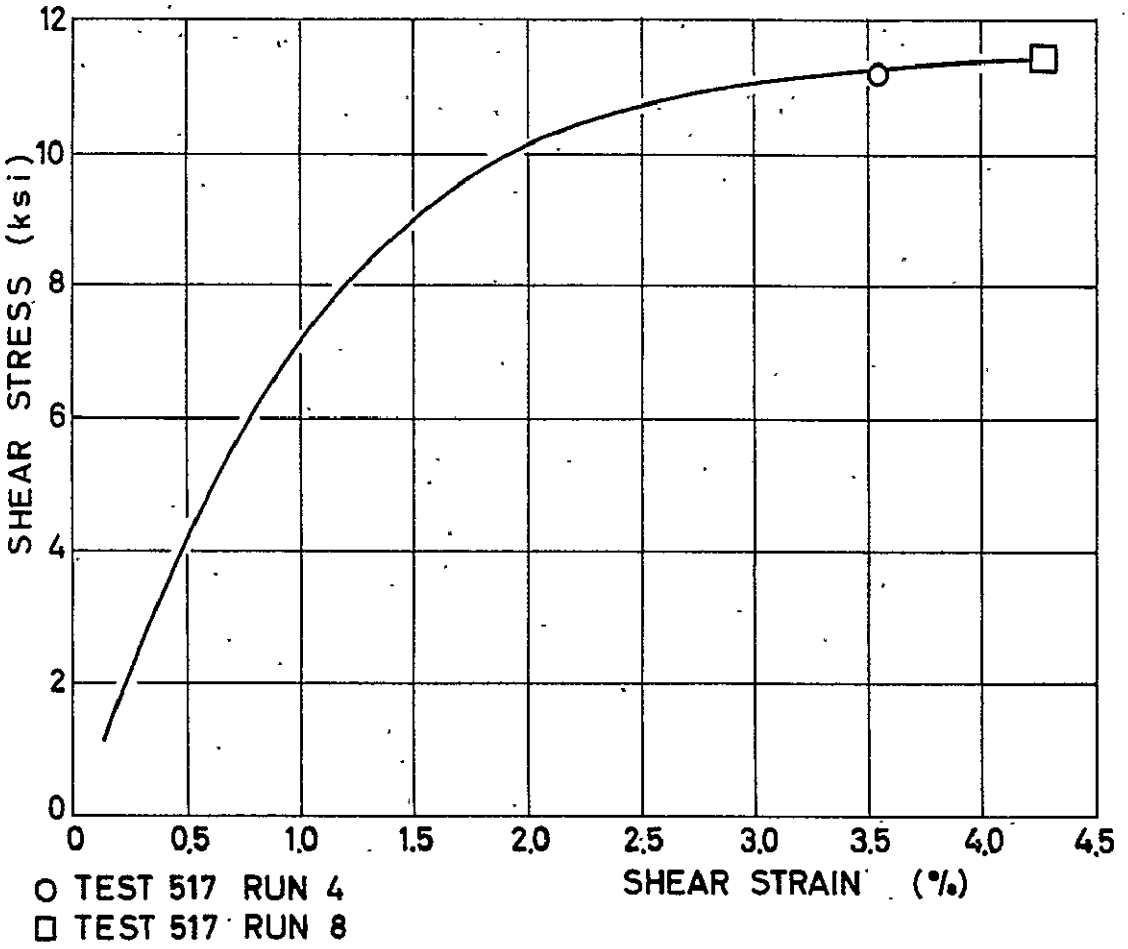


FIG.17C SHEAR RESPONSE OF ±45° AVCO 5505/5.6 MIL BORON-EPOXY LAMINATES



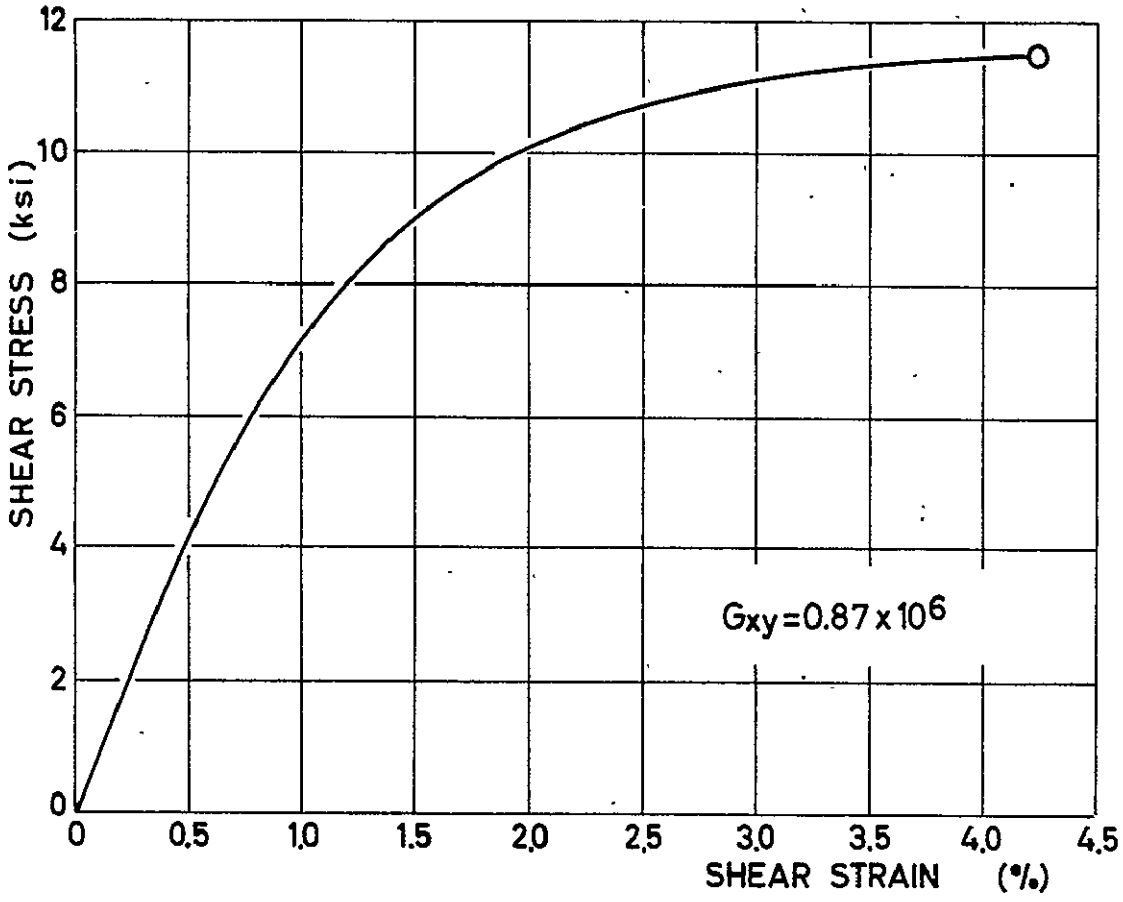
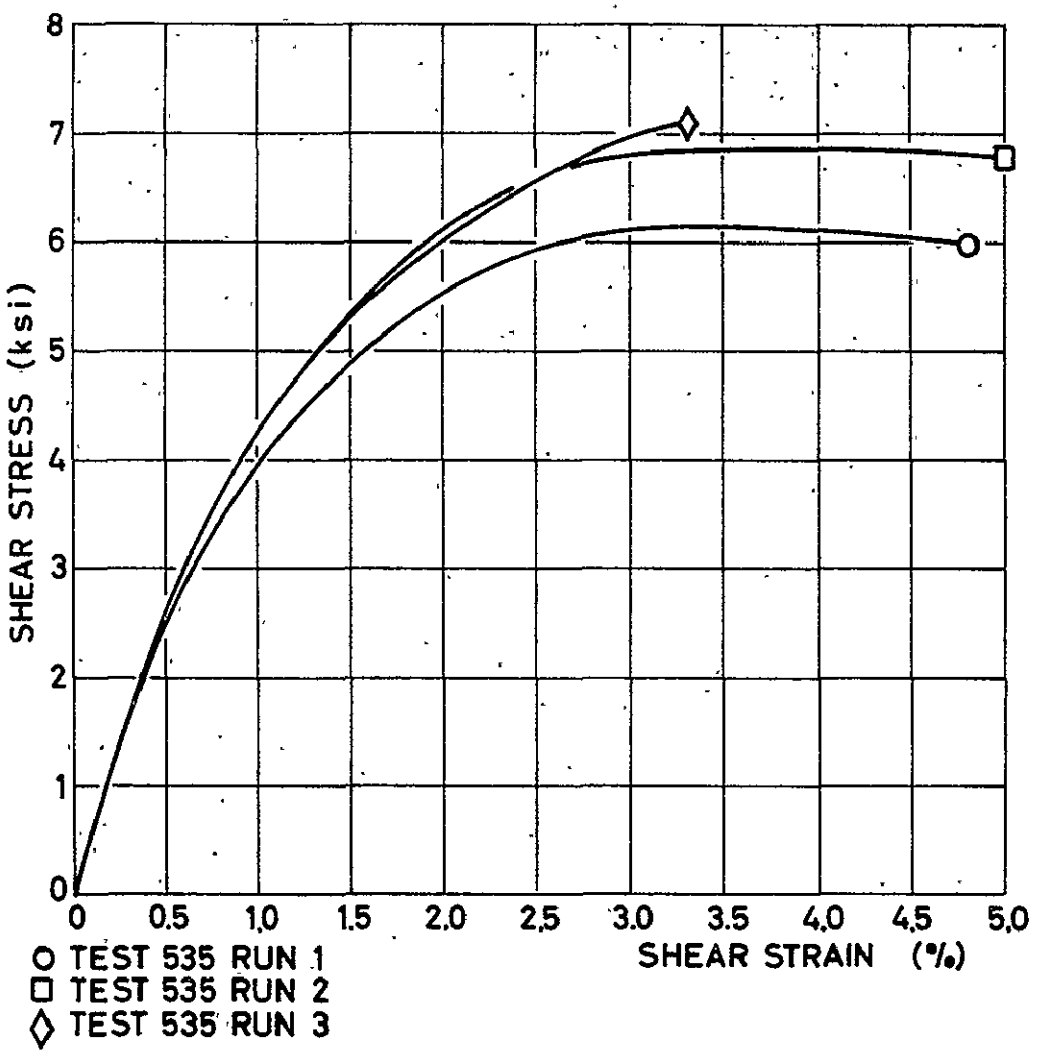


FIG. 18A SHEAR RESPONSE OF PLANAR SPECIMENS 0/90° B/EP



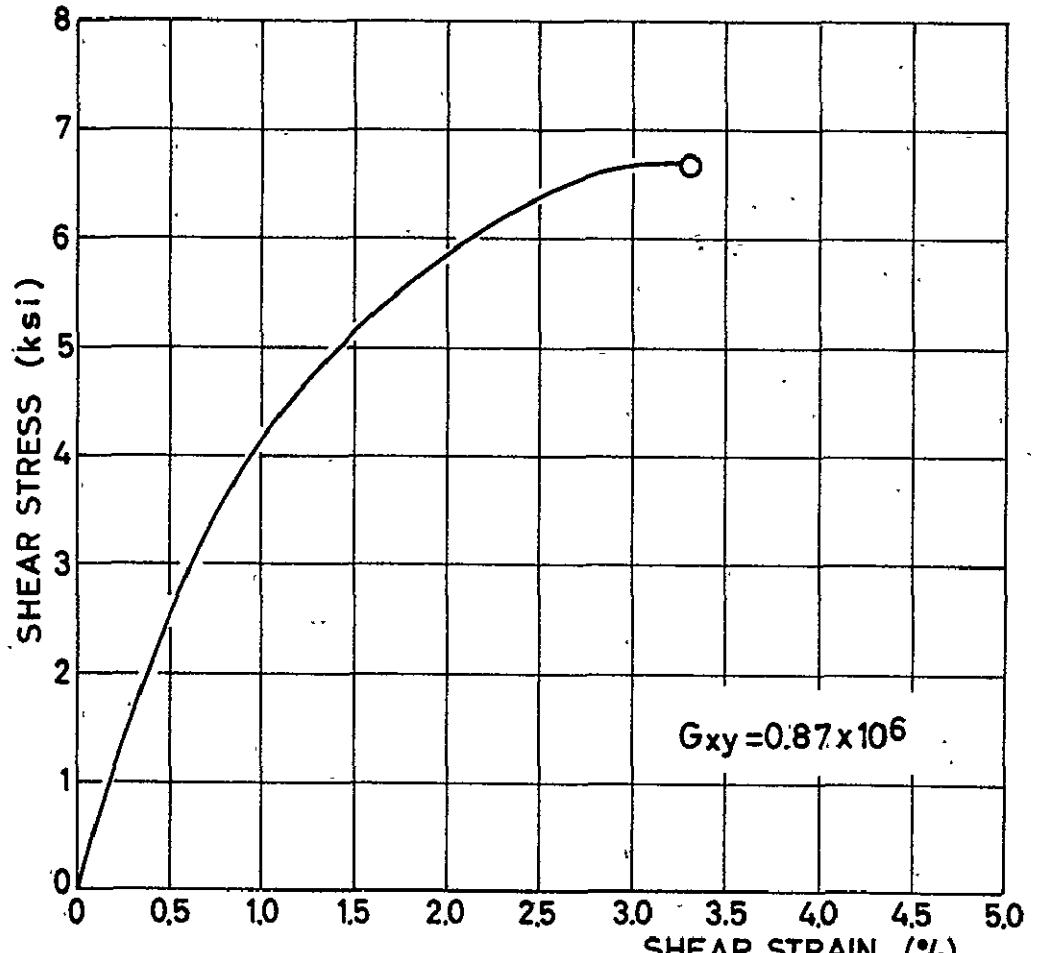


FIG. 18B SHEAR RESPONSE OF TUBULAR SPECIMENS 0/90° B/EP

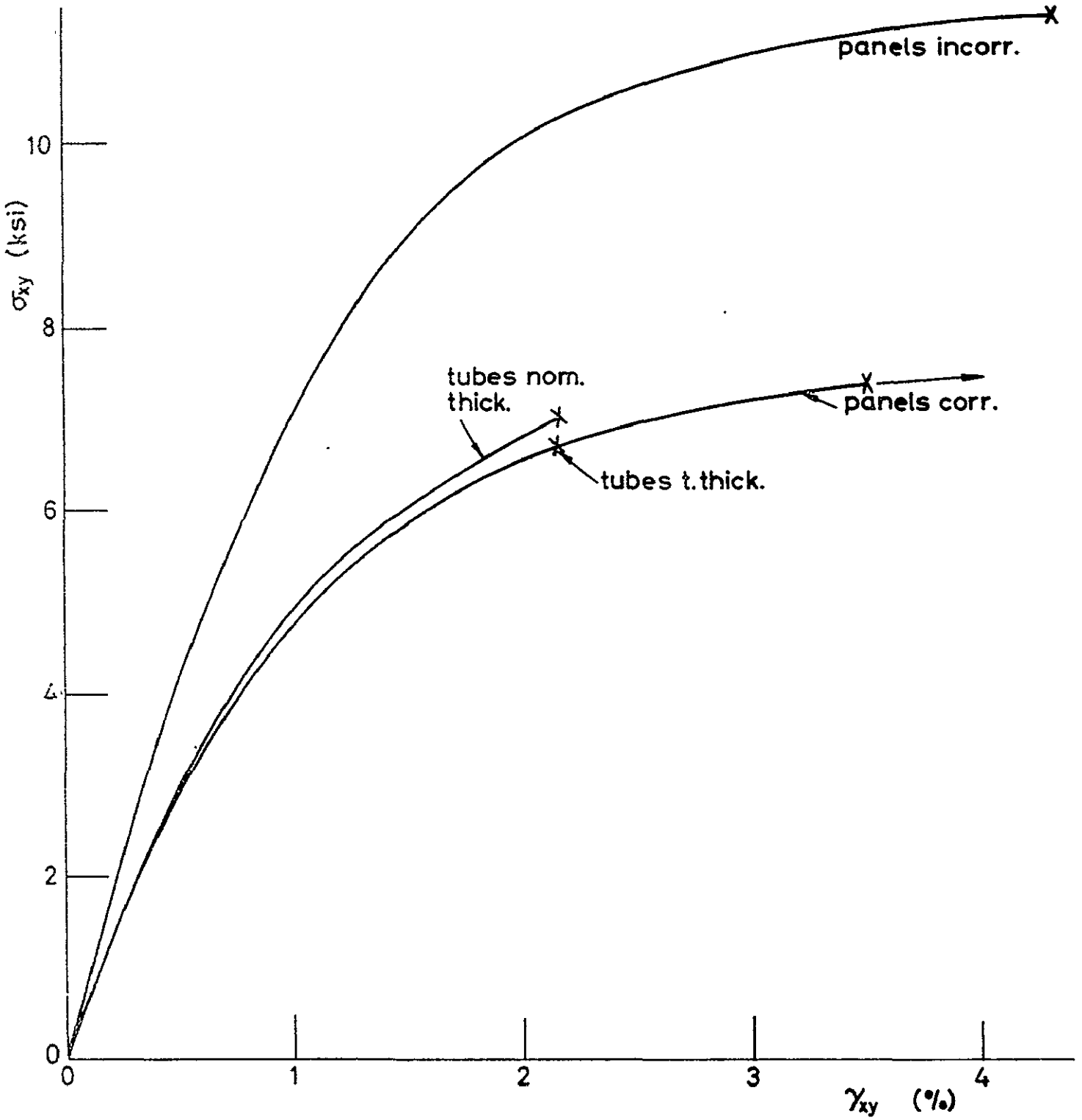
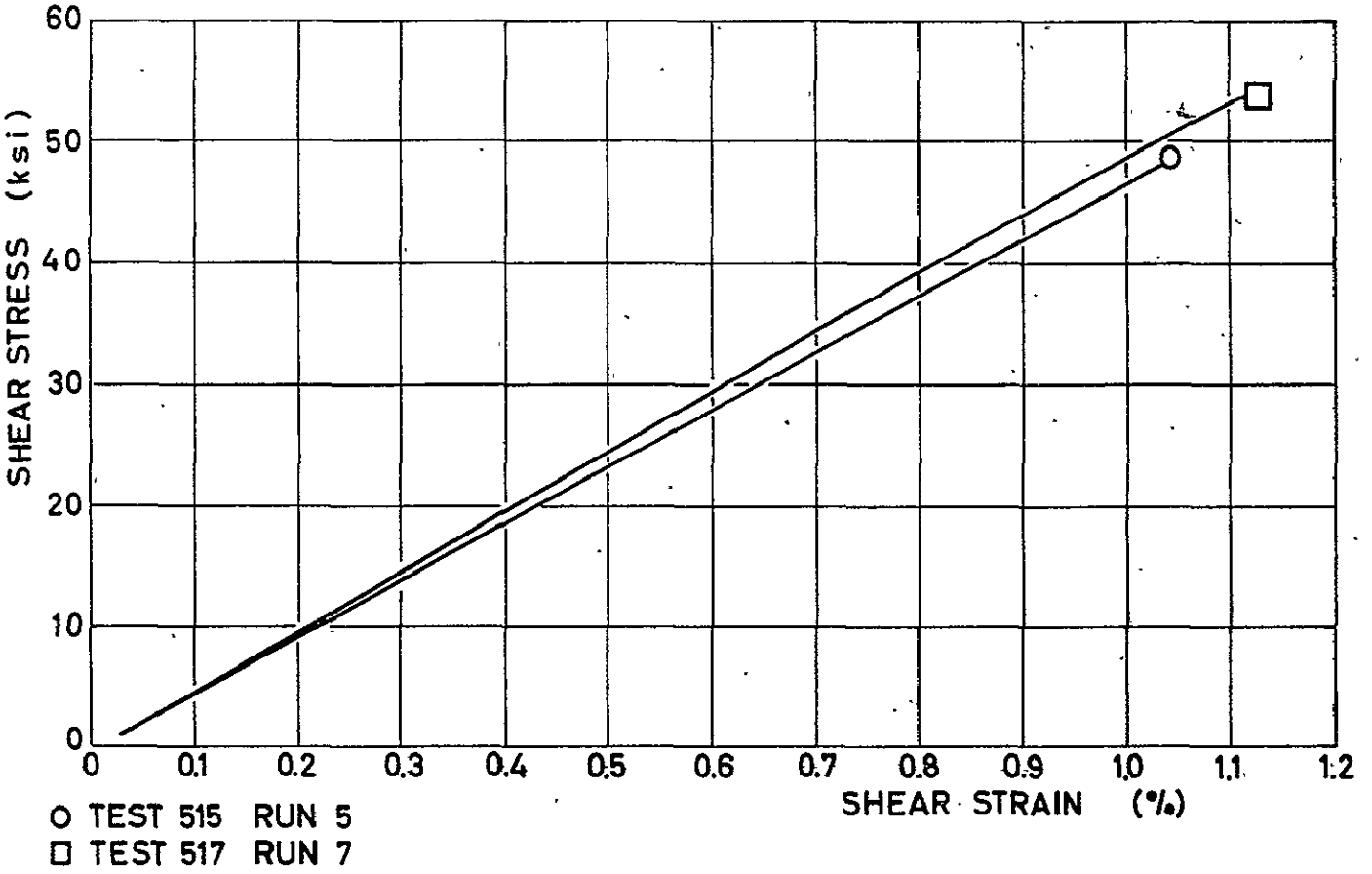


FIG. 18C SHEAR RESPONSE OF 0/90° AVCO 5505/5.6 MIL. BORON-EPOXY LAMINATES



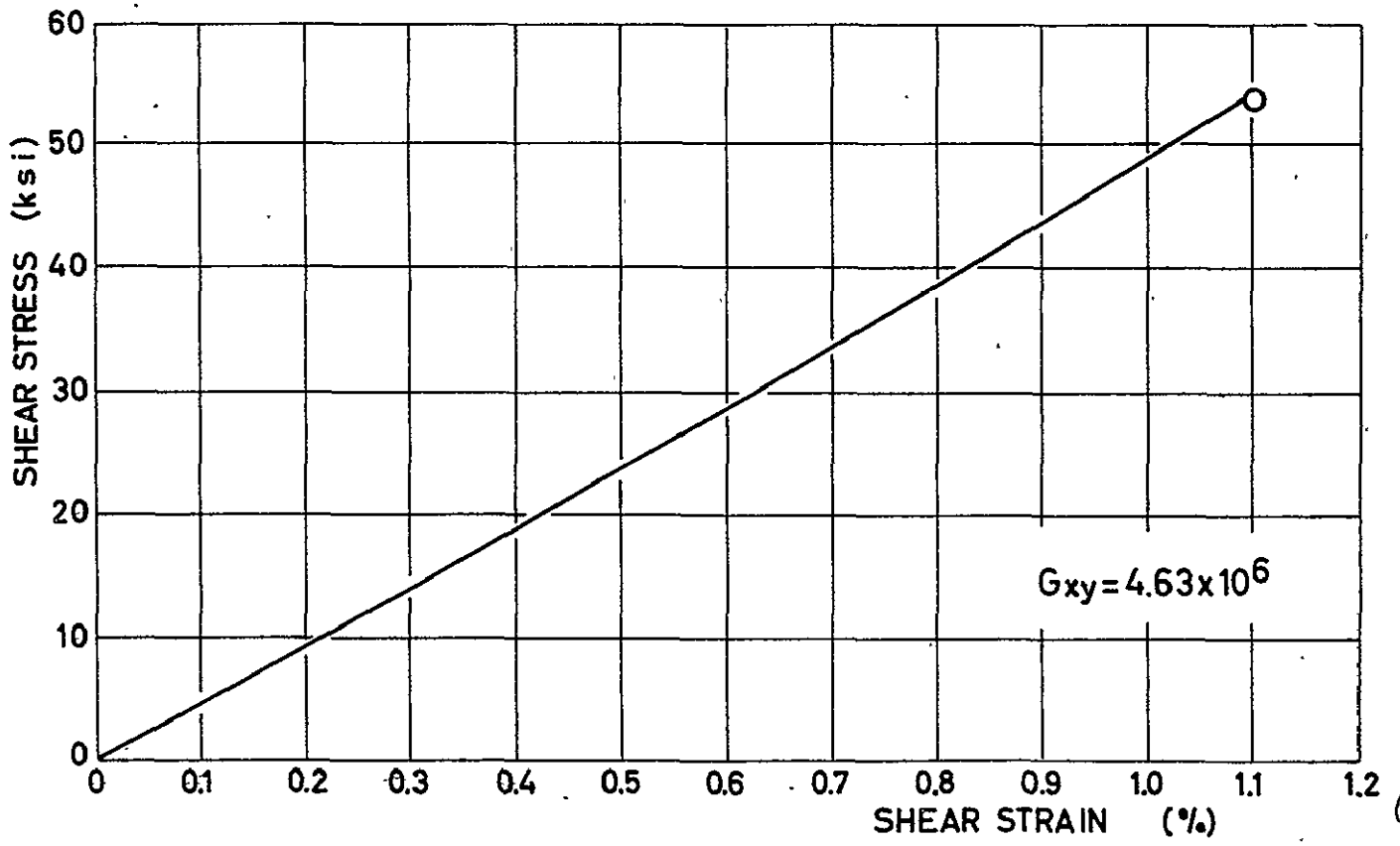
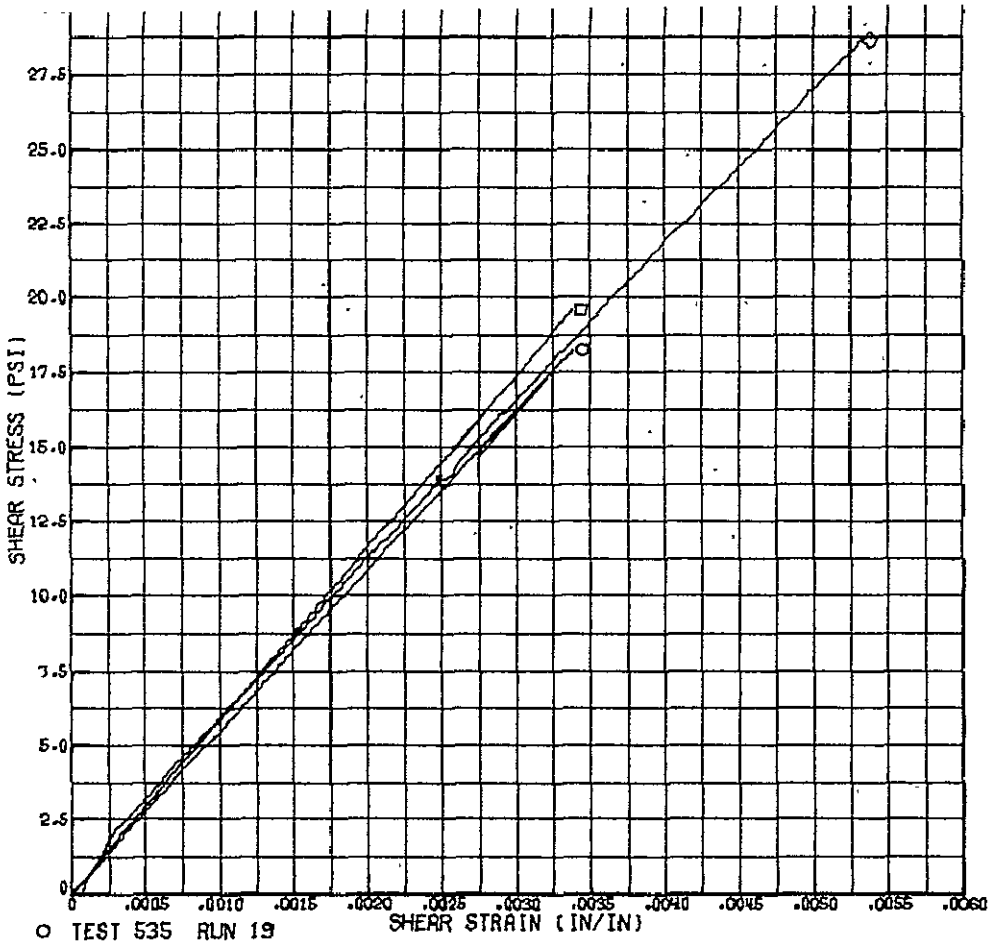
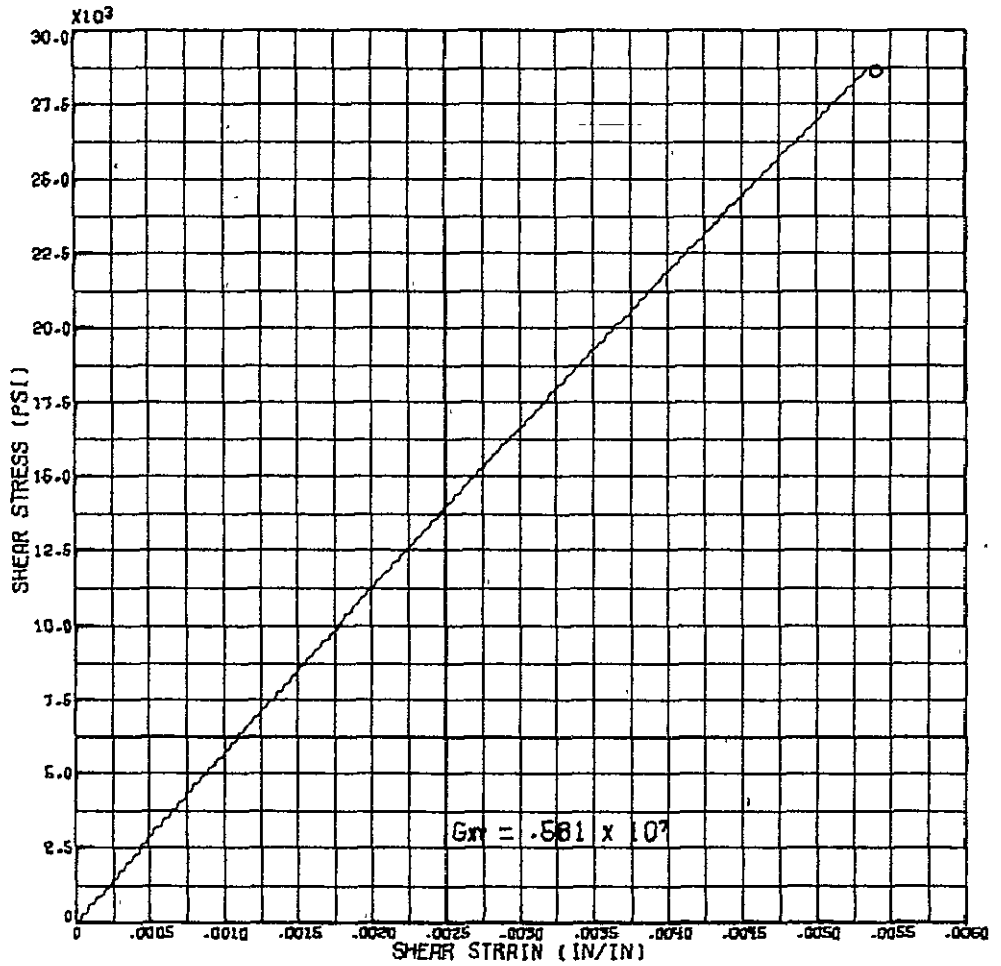


FIG. 19A SHEAR RESPONSE OF PLANAR SPECIMENS 0/±45/90° B/EP


SHEAR STRESS (PSI)
SHEAR STRAIN (IN/IN)
○ TEST 535 RUN 19
□ TEST 535 RUN 21
◇ TEST 536 RUN 3


X10³
SHEAR STRESS (PSI)
SHEAR STRAIN (IN/IN)
Gxy = .581 x 10⁷

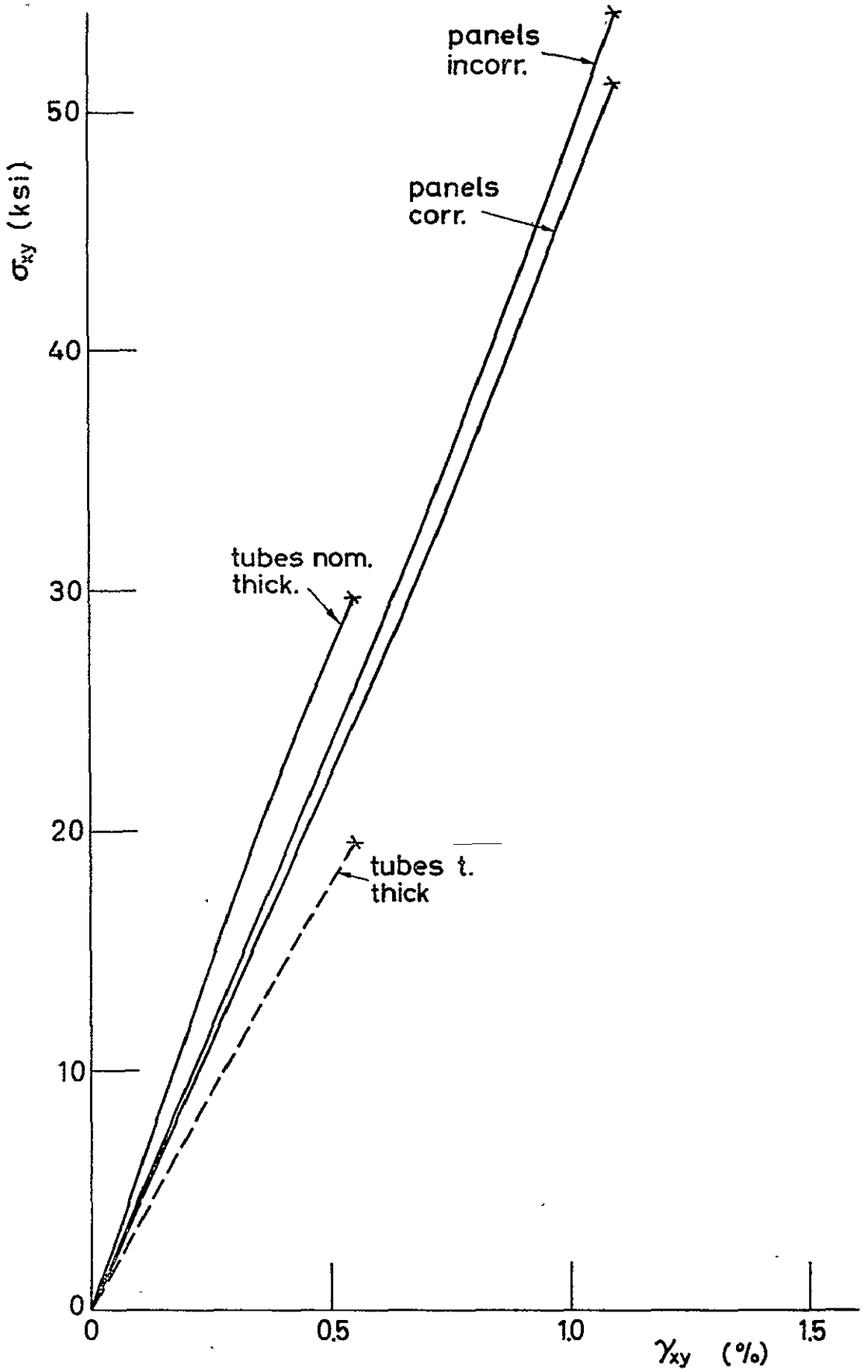


FIG. 19C SHEAR RESPONSE OF 0/±45/90° AVCO 5505/5.6 MIL BORON-EPOXY LAMINATES

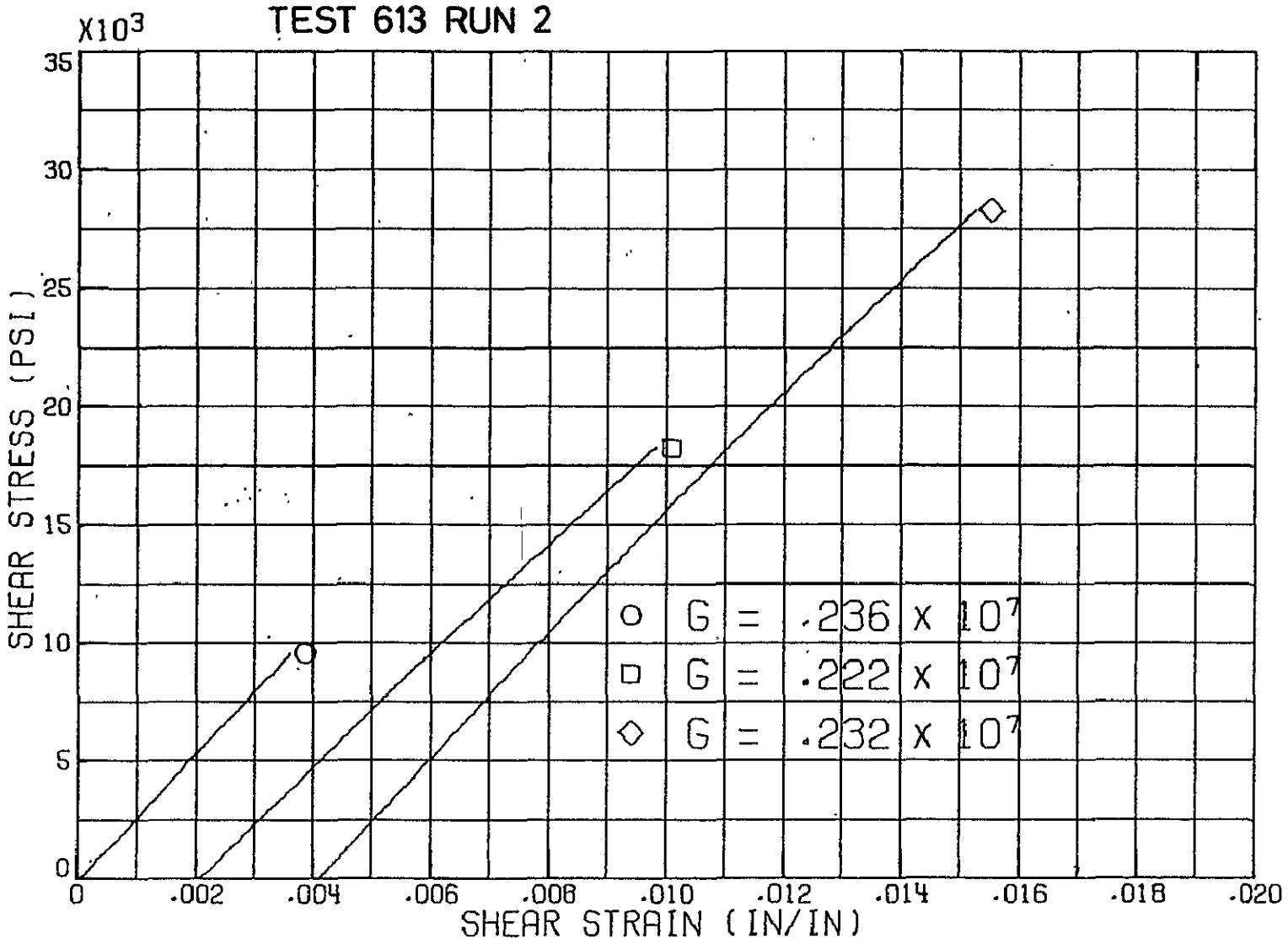


FIG. APA 11 - INFLUENCE OF LOADING AND UNLOADING ON RESPONSE OF SHEAR TUBES-[±15] GR/EP

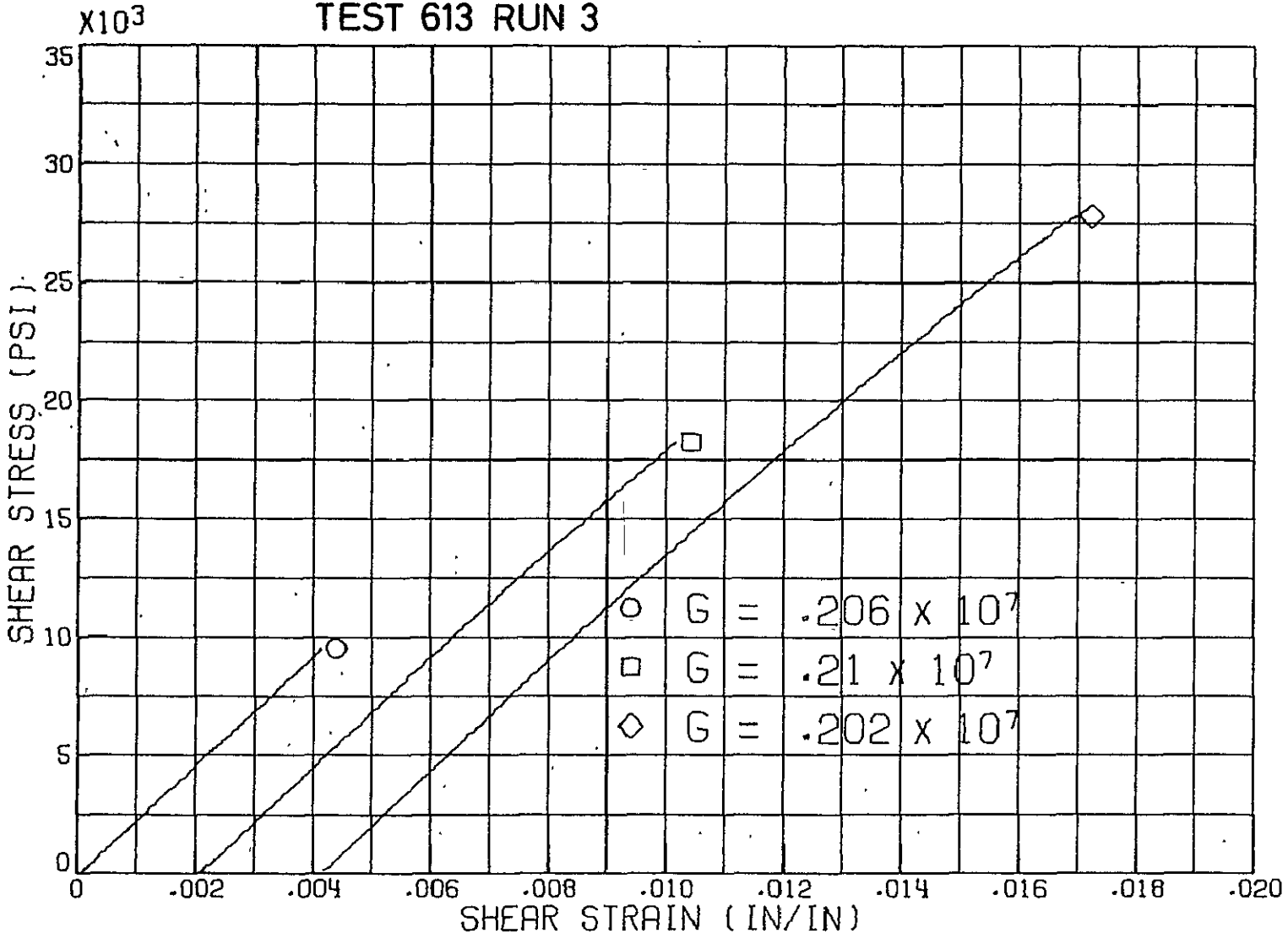


FIG. APA 1II -INFLUENCE OF LOADING AND UNLOADING ON RESPONSE OF SHEAR TUBES-[±15] GR/EP

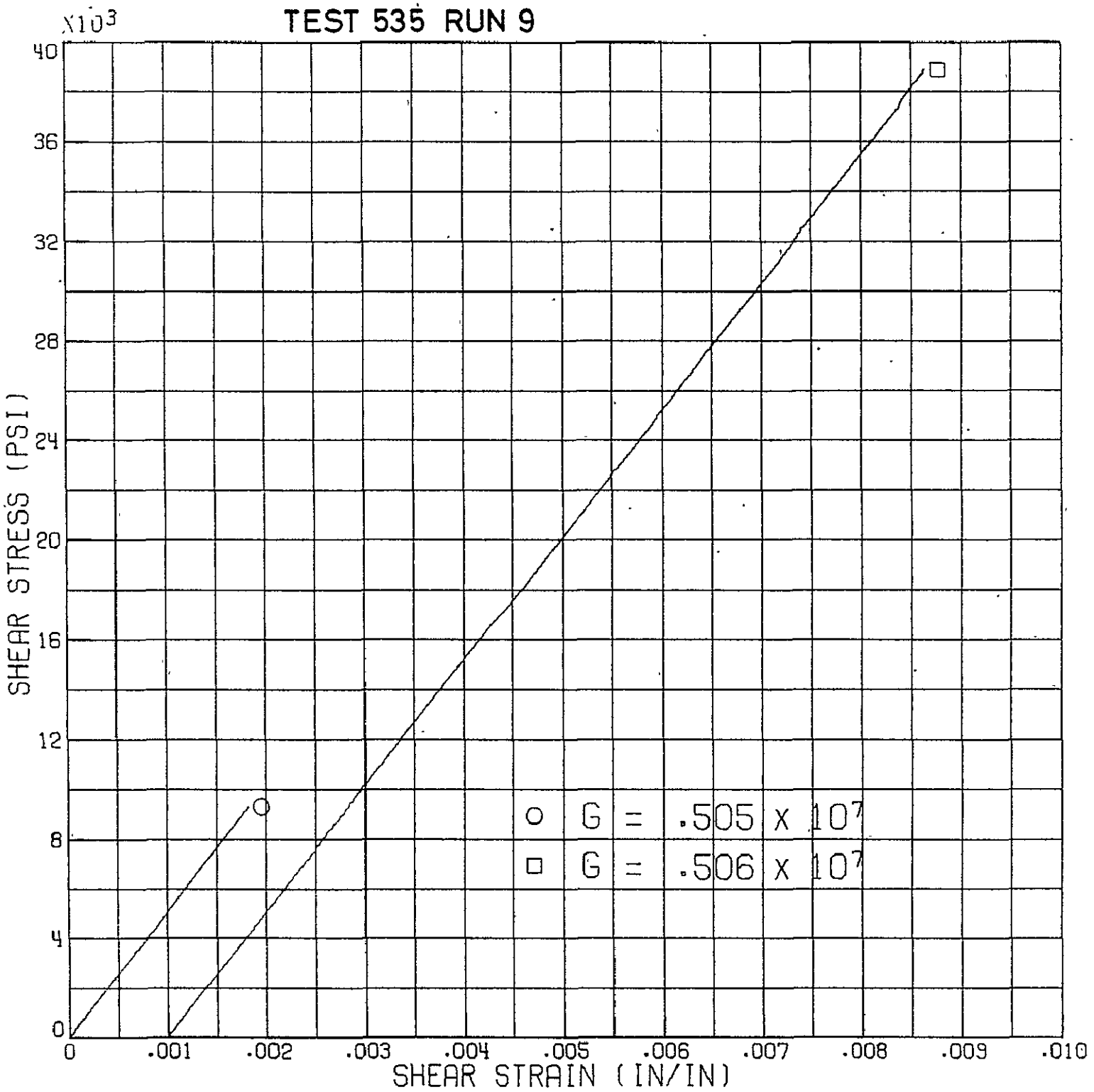


FIG. APA 21 -INFLUENCE OF LOADING AND UNLOADING ON RESPONSE OF SHEAR TUBES-[±30] GR/EP

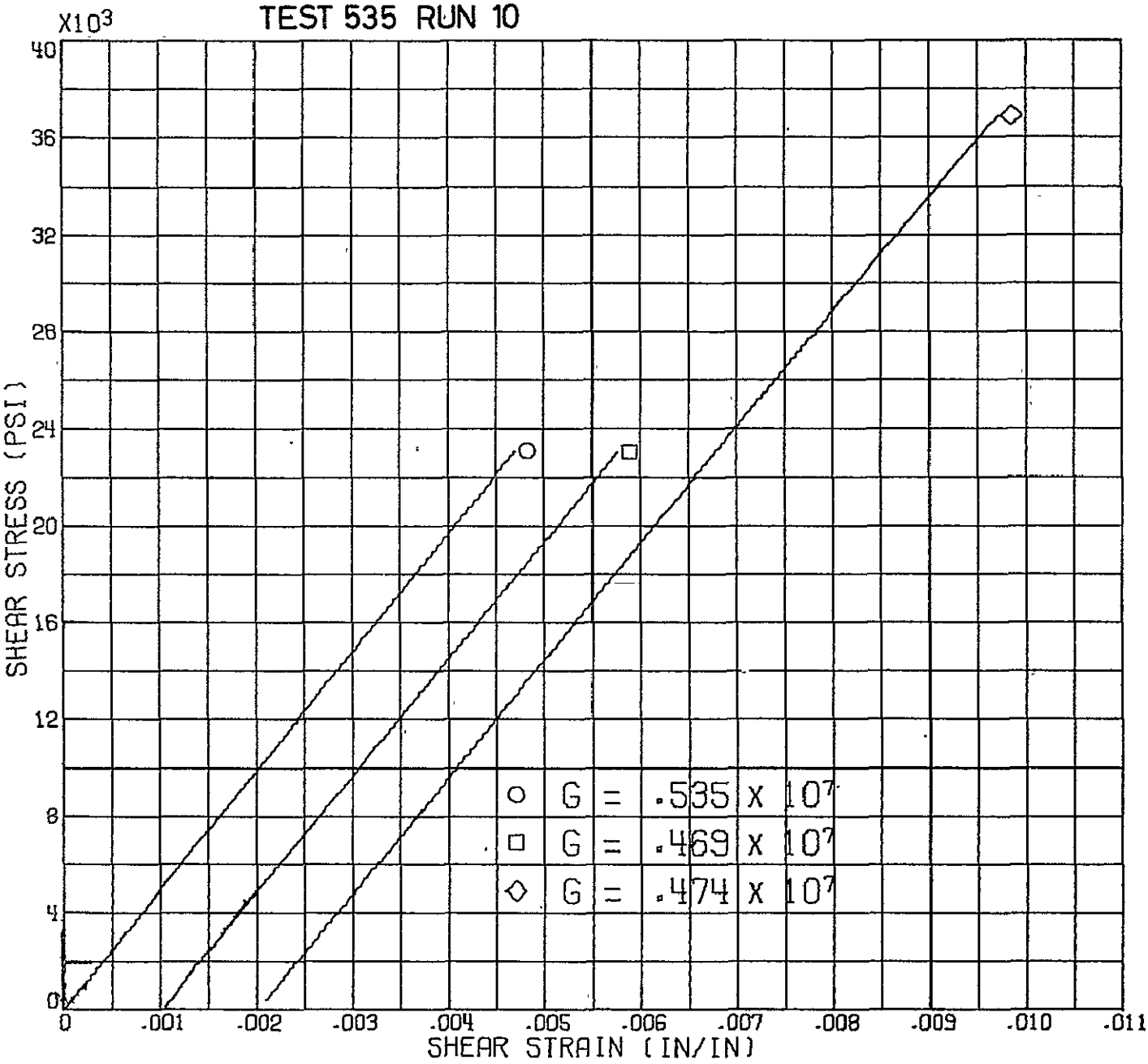


FIG. APA 2 II -INFLUENCE OF LOADING AND UNLOADING ON RESPONSE OF SHEAR TUBES-[±30] GR/EP

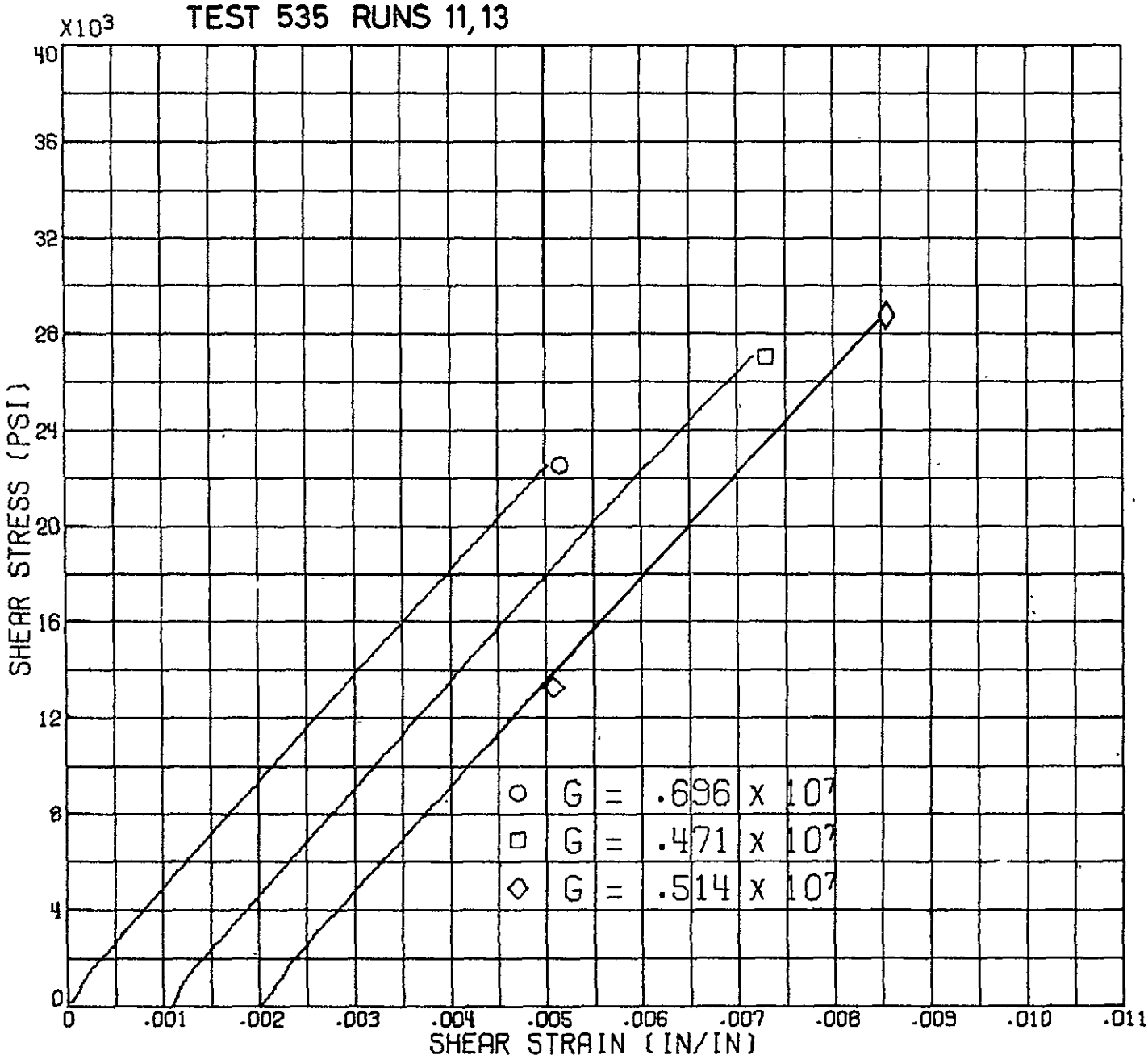


FIG. APA 2 III - INFLUENCE OF LOADING AND UNLOADING ON RESPONSE OF SHEAR TUBES-[±30] GR/EP

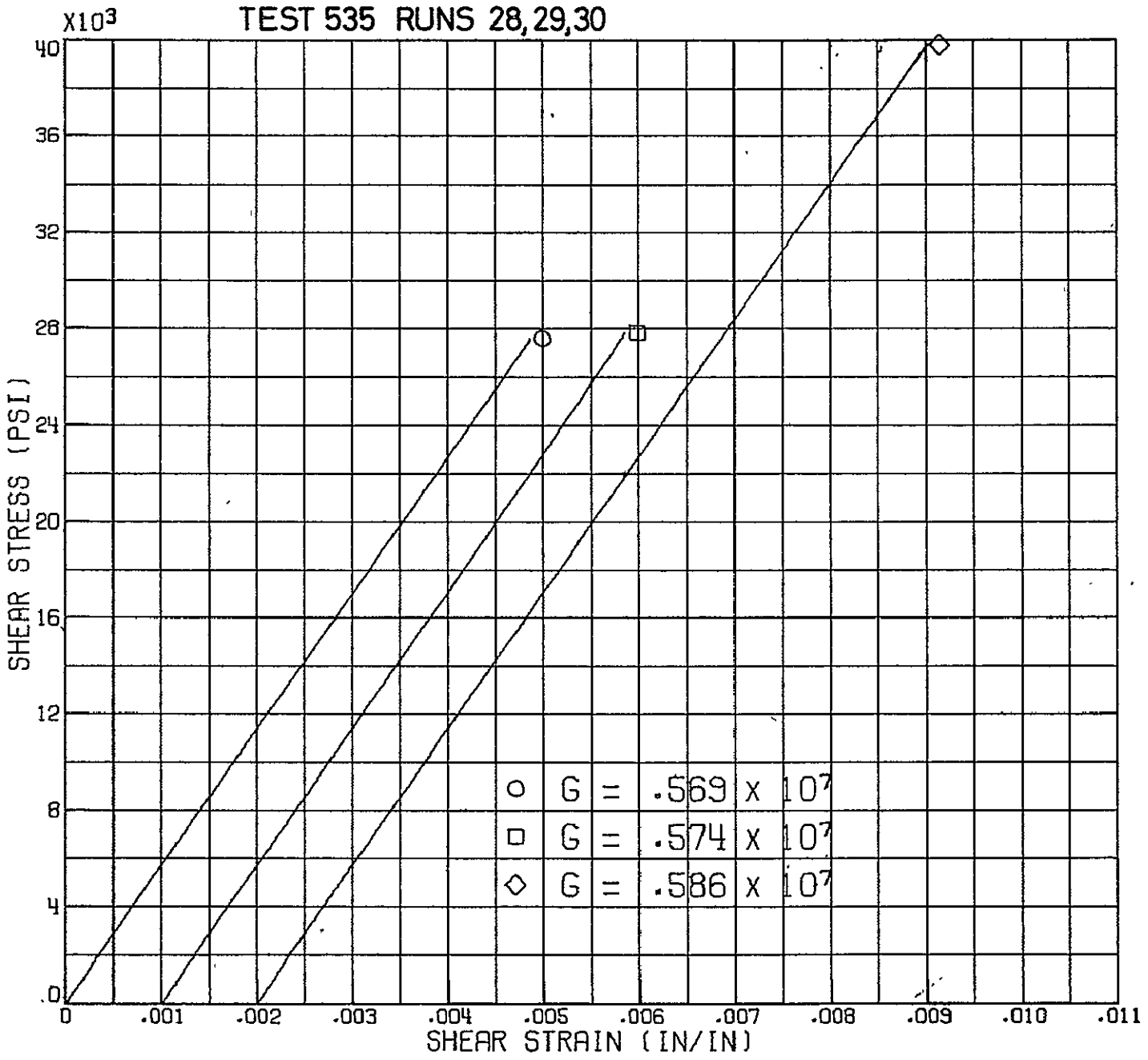


FIG. APA 3 - INFLUENCE OF LOADING AND UNLOADING ON RESPONSE OF SHEAR TUBES-[±45] GR/EP

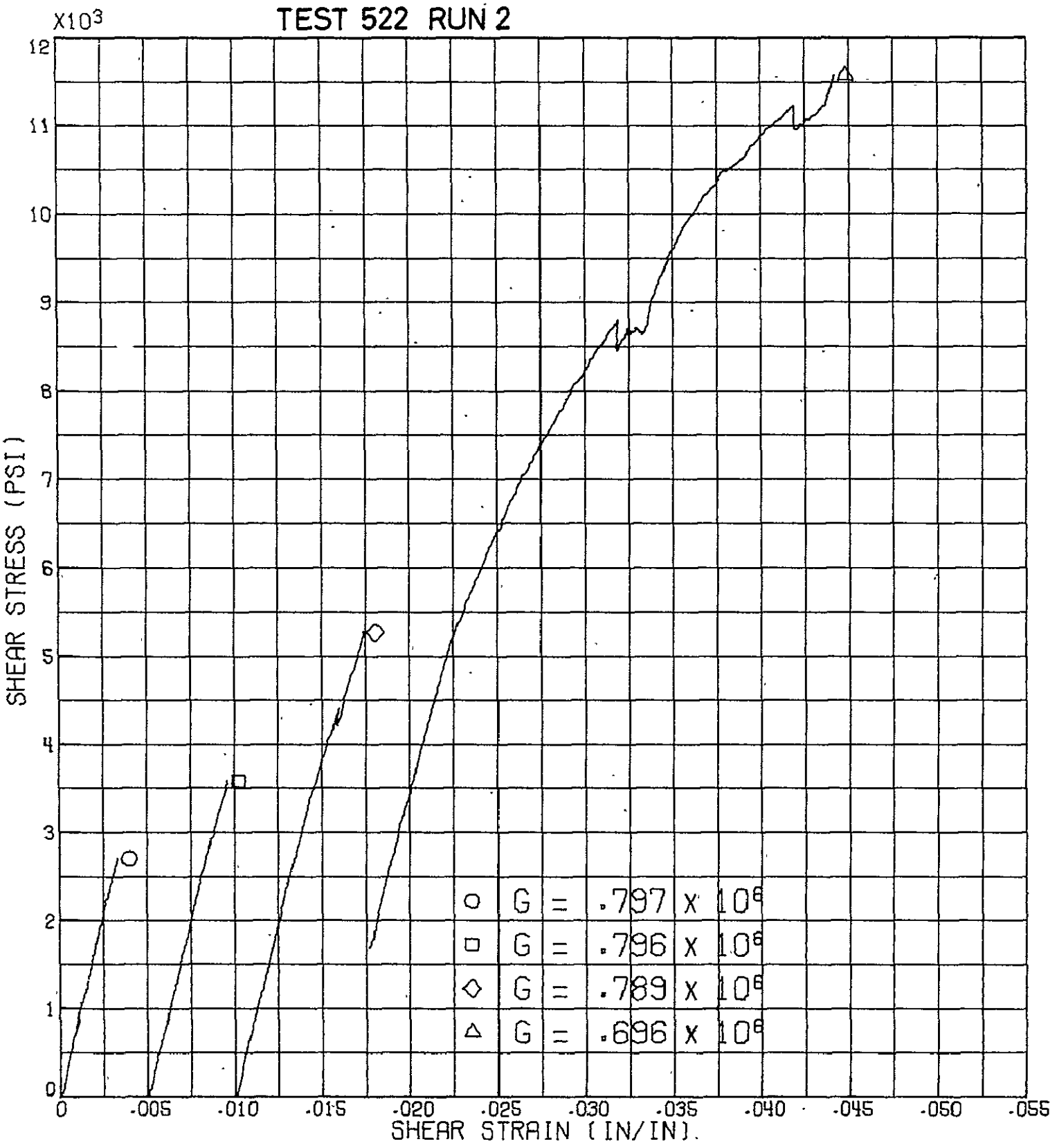


FIG. APA 41 -INFLUENCE OF LOADING AND UNLOADING ON RESPONSE OF SHEAR TUBES-[0/90] GR/EP 77

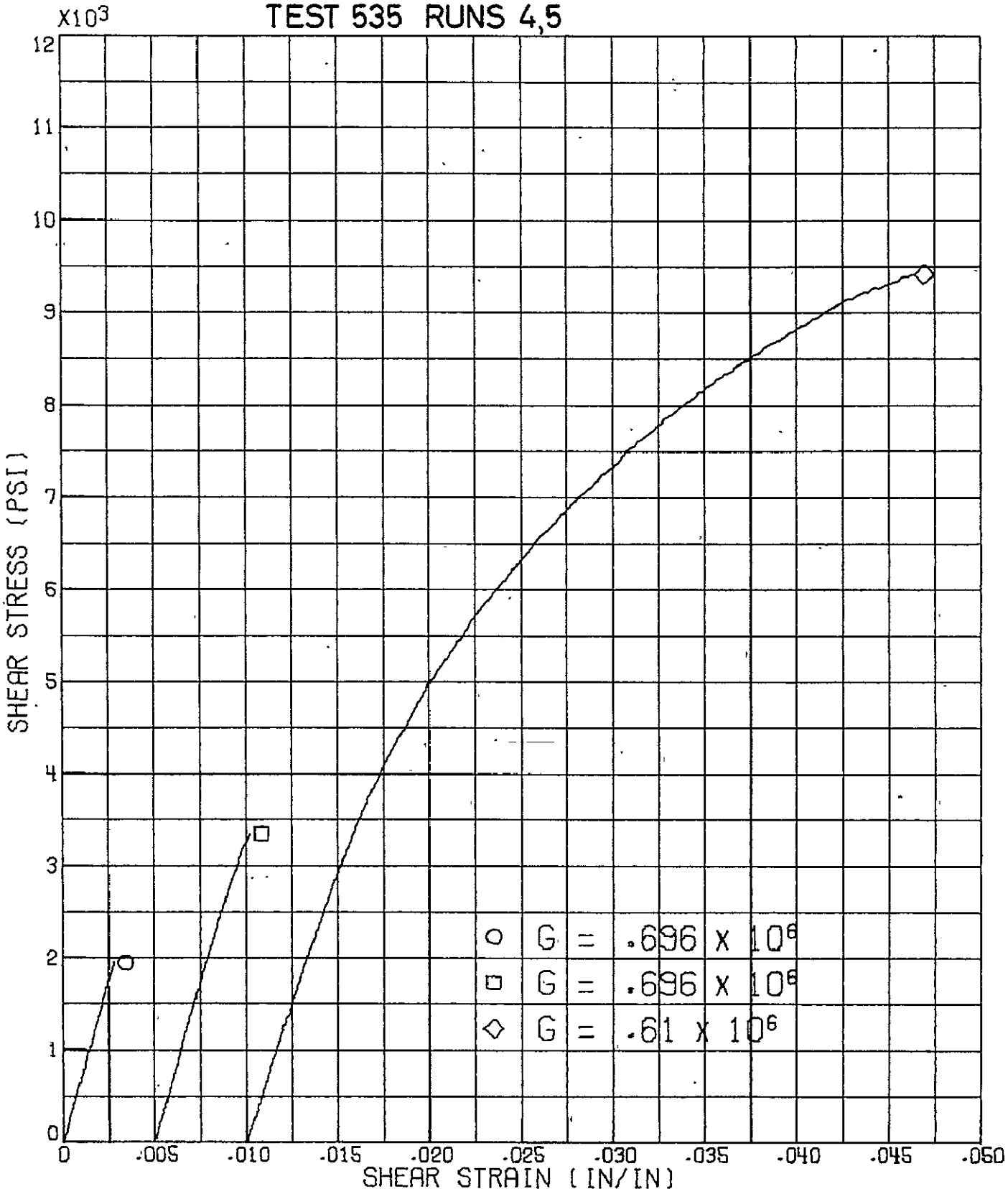


FIG. APA 4II -INFLUENCE OF LOADING AND UNLOADING ON RESPONSE OF SHEAR TUBES-[0/90] GR/EP

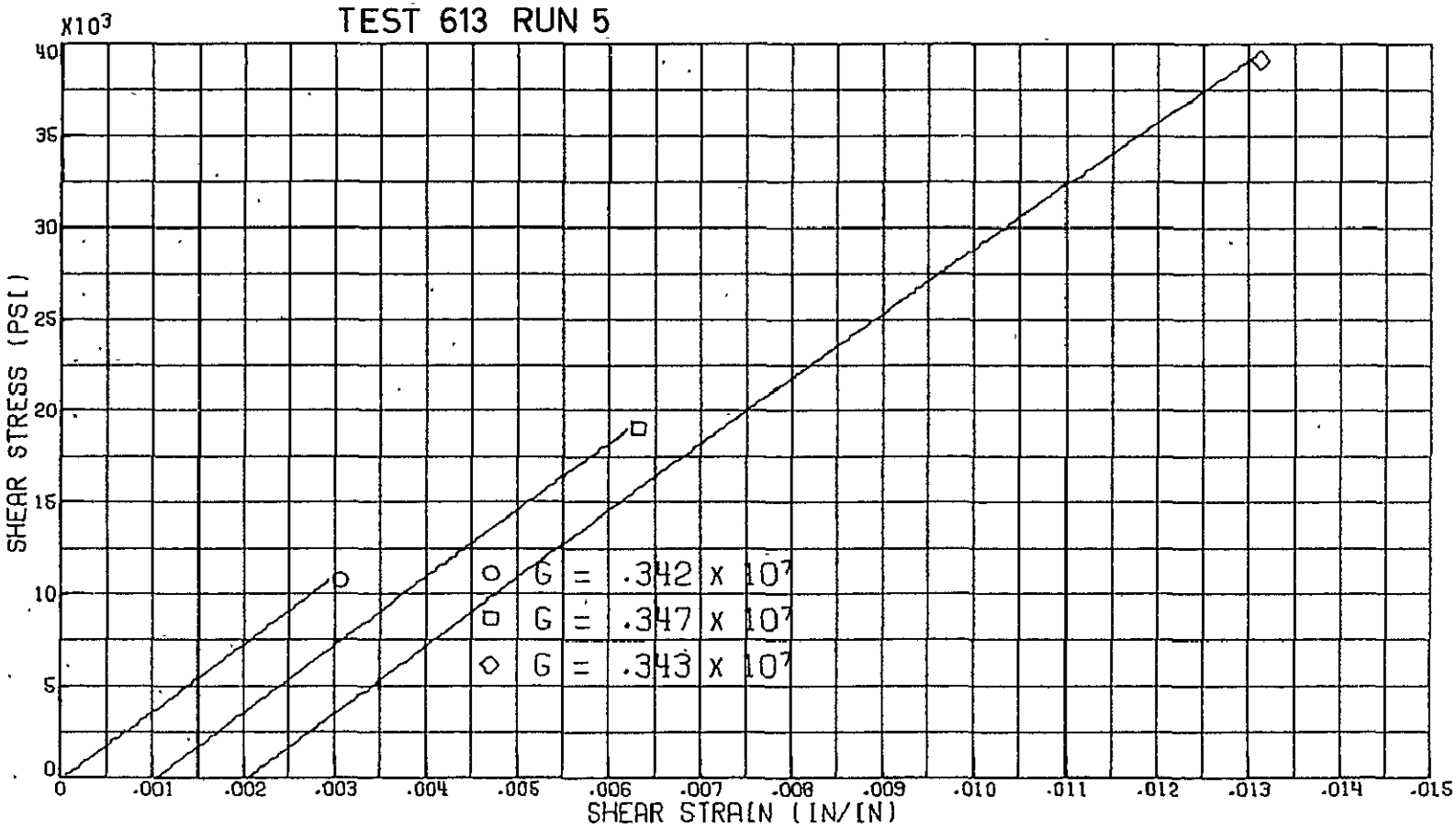


FIG. APA 5I -INFLUENCE OF LOADING AND UNLOADING ON RESPONSE OF SHEAR TUBES-[0/±45/90] GR/EP

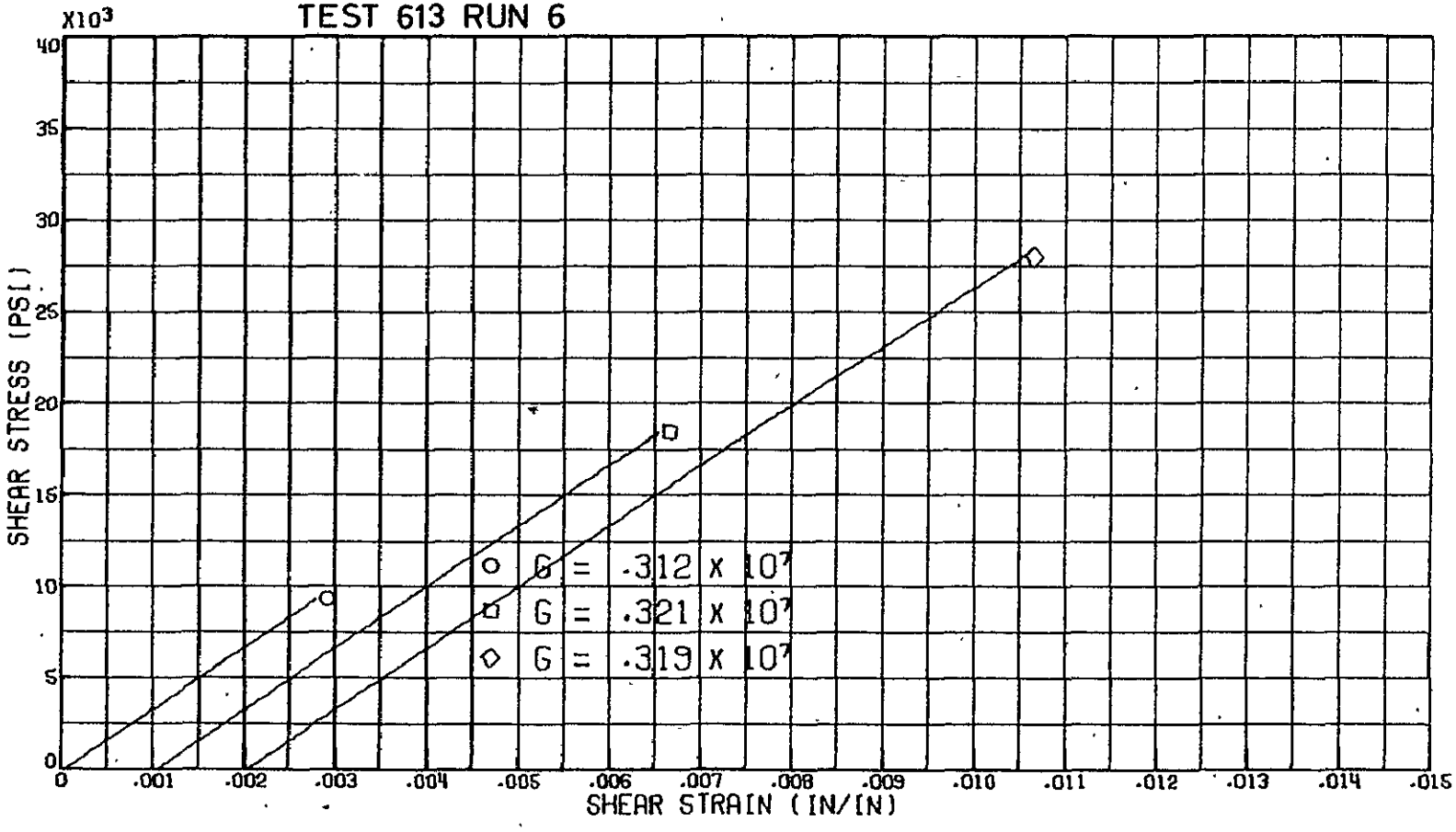


FIG. APA 5 II -INFLUENCE OF LOADING AND UNLOADING ON RESPONSE OF SHEAR TUBES-[0/±45/90] GR/EP

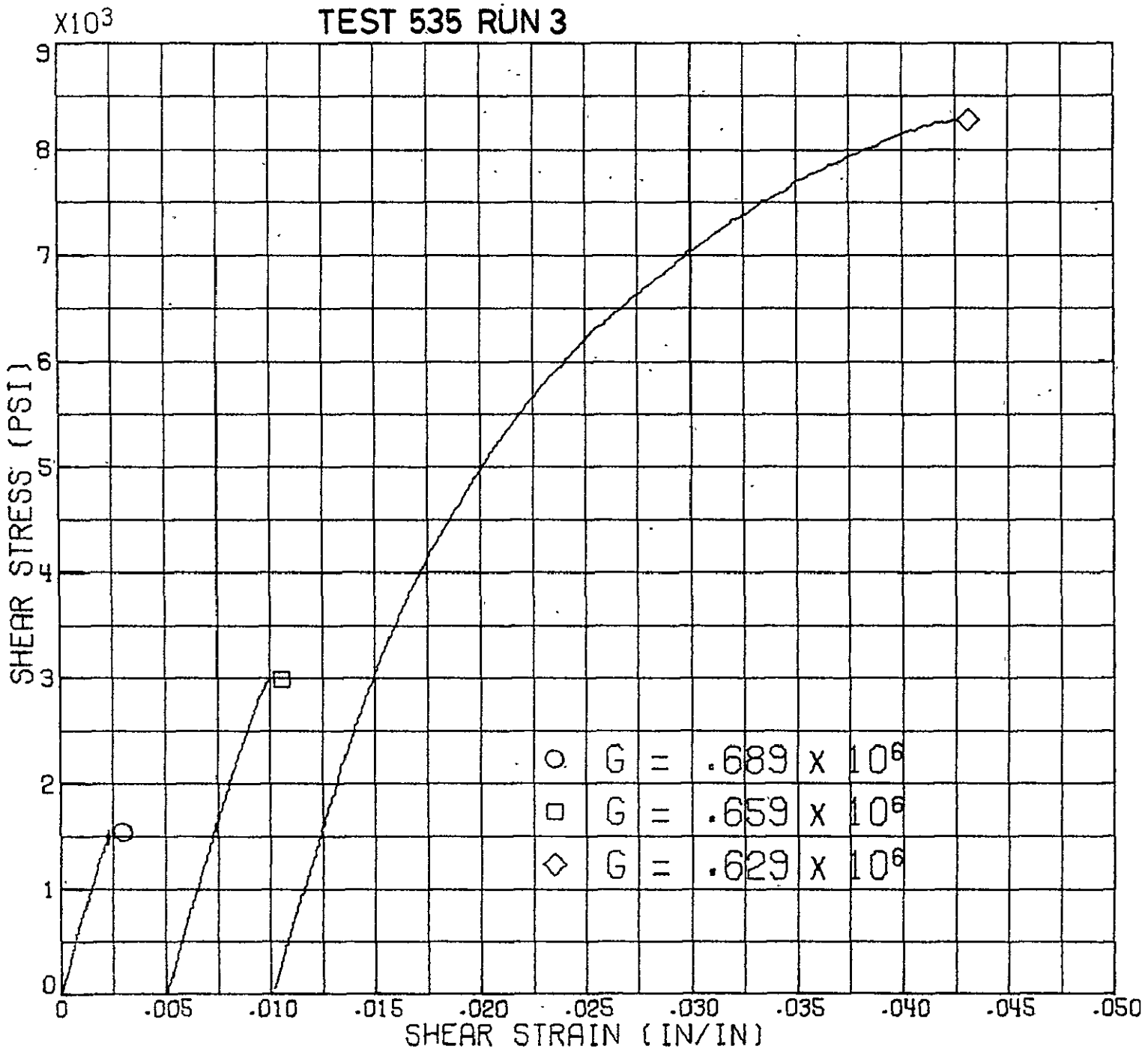


FIG. APA 6 -INFLUENCE OF LOADING AND UNLOADING ON RESPONSE OF SHEAR TUBES-[0/90] B/EP